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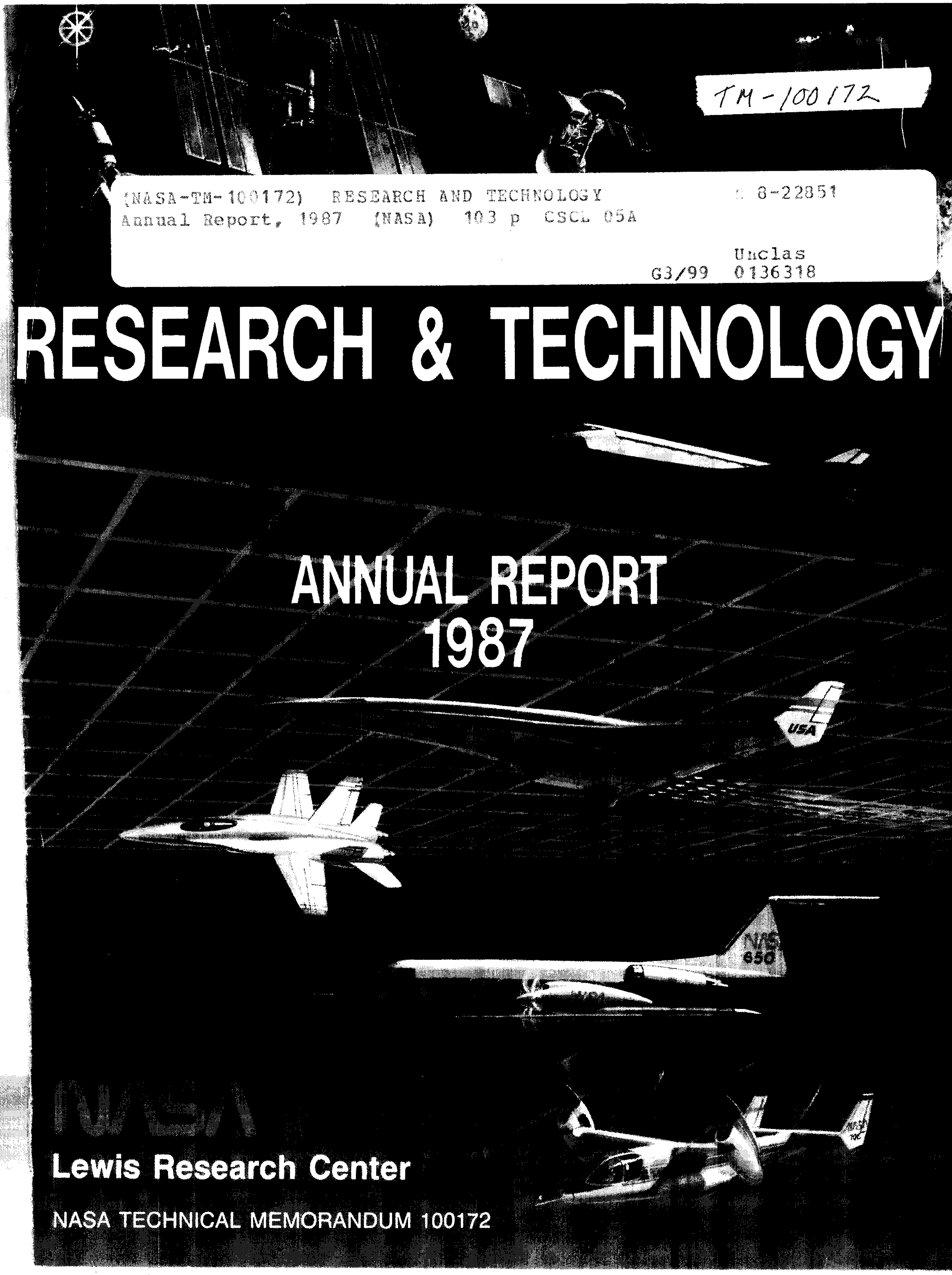
RESEARCH & TECHNOLOGY



ANNUAL REPORT 1987

Lewis Research Center

NASA TECHNICAL MEMORANDUM 100172

Contents

TM- 100172

Introduction

This report selectively summarizes the NASA Lewis Research Center's research and technology accomplishments for fiscal year 1987. It comprises approximately 100 short articles submitted by staff members of the technical directorates. The report is organized into four major sections: Aeronautics, Aerospace Technology, which includes space communications, Space Station Systems, and Computational Support. A table of contents by subject has been developed to assist the reader in finding articles of special interest.

This report is not intended to be a comprehensive summary of all the research and technology work done over the past fiscal year. Most of the work is reported in Lewis-published technical reports, journal articles, and presentations prepared by Lewis staff or by contractors. In addition, university grants have enabled faculty members and graduate students to engage in sponsored research that is reported at technical meetings or in journal articles.

For each article in this report a Lewis contact person has been identified, and where possible, a reference document is listed so that additional information can be easily obtained. The diversity of topics attests to the breadth of research and technology being pursued and to the skill mix of the staff that makes this possible. Your comments and inquiries are welcome. For general information about this report please contact Robert W. Graham at (216) 433–5828 or FTS 297–5828.

John M. Klineberg
Director

Advanced Planning and Analysis

Supersonic/Hypersonic Commercial Transport Propulsion

Lewis is sponsoring studies both *in-house and on contract to* identify unique propulsion systems for high-speed (Mach 3 to 5) commercial transports. An unconventional engine, the supersonic throughflow-fan turbofan, is among the unique cycles under study. This engine incorporates a single-stage supersonic throughflow fan. This type of fan has supersonic axial Mach numbers at the fan face and the stator exit, achieving high pressure ratios in a single stage. It eliminates the need for a subsonic inlet diffuser and thus reduces inlet length and weight by up to 50 percent over conventional supersonic inlets. The shorter inlet also reduces drag and improves pressure recovery.

Completed studies have included a Mach 3 high-speed transport carrying 290 passengers. The study results show that, compared with conventional turbofans of the same technology level, the supersonic fan engine reduces the installed specific fuel consumption by 12 percent, could reduce propulsion system weight by 25 percent, and thus could extend range by 25 percent (to ~6250 n mi).

To further investigate this engine concept, Pratt & Whitney Aircraft is performing additional studies for several aircraft applications. Model aerodynamic tests are planned at Lewis to evaluate fan performance and operating characteristics. Studies are also continuing to investigate alternative supersonic fan cycles, aircraft, and missions.

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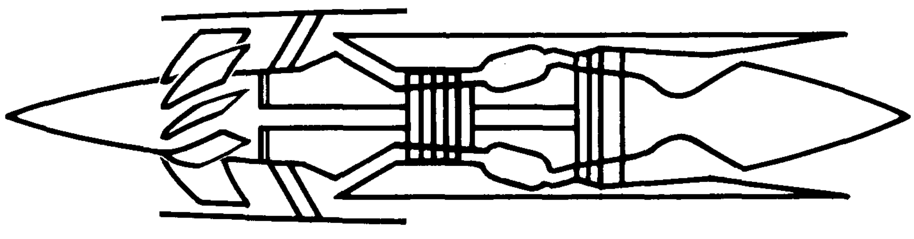

Turbofan with supersonic throughflow fan

CD-86-19615

Instrumentation and Control Technology

Ramp/DC Integration Technique for Capacitance Blade-Tip Clearance Measurements

Measurement of blade-tip clearance is important to the design, development, and operation of fans, compressors, and turbines. During the design phase computational codes are generated to predict engine behavior under operational conditions. The accuracy of these codes must be verified by comparing them with reliable experimental data. The clearance between the turbine blade tip and the shroud is one of the important factors that govern the efficiency of a turbine engine. Hence Lewis has sought to obtain reliable, accurate data on this clearance by using a capacitance probe.

As the blade passes under the probe tip, the capacitance $C_b(t)$ between the blade tip and the inner electrode of the probe changes as a function of the gap geometry. If C_o represents any static capacitance that is present across $C_b(t)$, the capacitance at any moment is given by $C(t) = C_o + C_b(t)$. To reduce the effect of C_o, a reference channel containing feedback resistance R_2 and C_o is introduced. The output of the signal channel is subtracted from the reference channel and multiplied by G to obtain the differential voltage V_d. The integrated output V_o is proportional to $C_b(t)$, which in turn is related to the clearance.

The ramp/dc integration technique can measure clearance with high-temperature sensors. Furthermore it has static calibration capability, has good dynamic response for high-speed rotors, and is immune to connecting-cable vibration.

In addition, capacitance probes are low in cost relative to other types of instrumentation and therefore attractive for multiple-probe installations.

The work was done in-house by Dr. Garimella R. Sarma, a National Research Council–NASA Resident Research Associate, and completed in June 1987.

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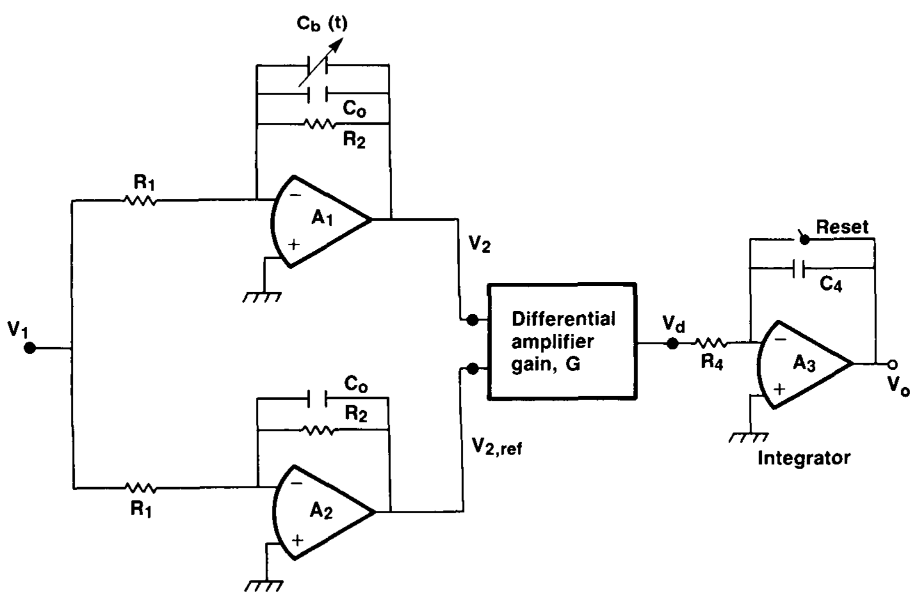

Implementation of ramp/dc integration technique

Four-Spot Laser Anemometer

Nonintrusive flow measurements near turbomachine surfaces require a laser anemometer with special qualities. The optimum anemometer would have a large flow acceptance angle for measuring wide-flow-angle variations and also have high spatial selectivity to limit the amount of unwanted flare light scattered from surfaces reaching the detector. A new modified time-of-flight anemometer (TOFA), called the four-spot TOFA, has been constructed and tested at Lewis in cooperation with Case Western Reserve University.

Because of their highly focused measurement volume TOFA systems have high spatial selectivity. The four-spot TOFA also uses elliptical spots to increase the flow acceptance angle and has a spatial lead-lag operator. The operator is implemented by using four spots in the measurement region. This coding of the measurement volume permits part of the signal processing to be done optically rather than electronically. Optical preprocessing simplifies the signal-processing electronics and enhances the measurement accuracy.

The four-spot system has been tested in particle sizing experiments, in boundary layer measurements, and in a warm burner facility. The system has shown superior measurement capabilities over conventional laser anemometers in hostile environments. A fiber-optic-based version of the four-spot TOFA is being designed for use in a large centrifugal compressor facility at Lewis.

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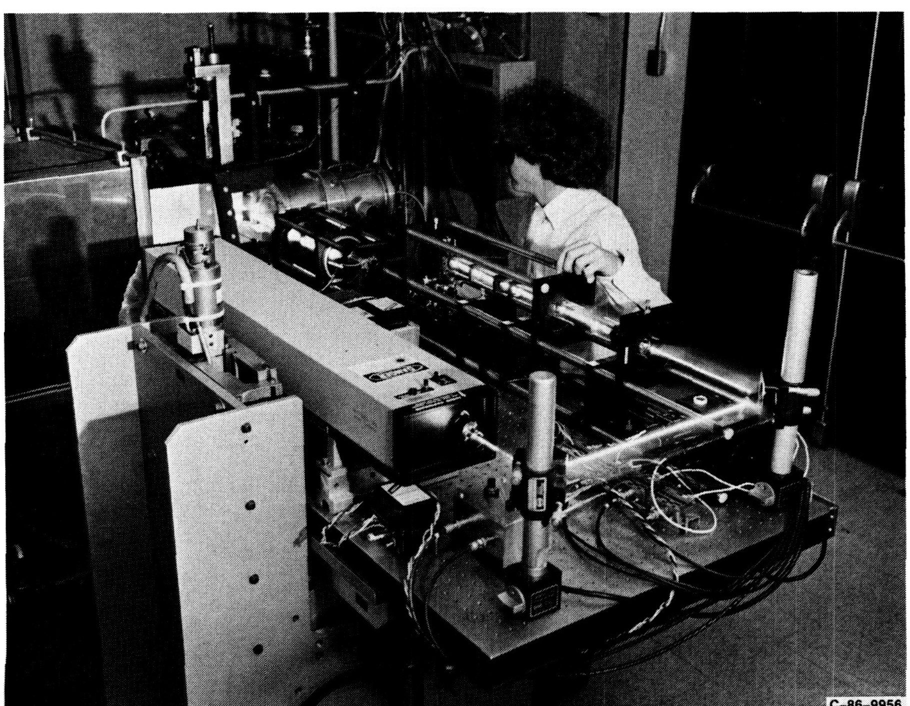

Four-spot, time-of-flight laser anemometer

Heat Flux Gage Calibration Laboratory

A new Lewis laboratory calibrates and durability tests heat flux gages operating at conditions of high heat flux, high temperature, and rapid thermal transients. This laboratory was developed to more thoroughly characterize the hostile environment in turbines driving space shuttle main engine (SSME) turbopumps. Severe thermal transients are believed to cause durability problems, such as material cracking, in the SSME turbines. Heat flux sensors placed in turbine components can aid in characterizing this environment by measuring surface heat flux. The heat flux data can then be used to verify analytical stress, boundary layer, and heat transfer design models. This research also has direct application to other aeropropulsion systems.

The laboratory is easy and safe to operate and is designed so that the researcher can try new ideas and get quick results. It has been demonstrated that the calibrator achieves high heat flux, rapid thermal transients, and high temperatures. The heat source is a 100-kW Vortek arc lamp. Heat flux over a range of about 1 to 6 MW/m^2 has been measured with an accuracy of $\pm$20 percent with special uncooled heat flux gages designed at Lewis. These heat flux values agree with those obtained with industrial water-cooled gages. Thermal transients as high as 700 K/sec and gage body temperatures of 1500 K have been measured. These heat flux levels, thermal transients, and gage temperature levels approach those that may occur in the SSME turbopump turbine environment (about 10 MW/m^2, 1000 K/sec, 1500 K). Computer codes are used to calculate the heat flux from the measured temperature history and temperature gradients within the gage bodies. A NASA report describing a physical and mathematical model for calculating heat flux and associated experimental error is in progress. Additional heat flux research is being done through a grant with Case Western Reserve University on the development of a rational basis for calibrating heat flux gages.

Research on heat transfer characteristics and the measurement accuracy of new miniature, high-response, high-temperature heat flux gages is being performed in the facility. The miniature gages are being developed in-house and under Lewis-sponsored contracts. This research focuses on the development of gages unique to special SSME requirements, but application to other aerospace systems is also being considered.

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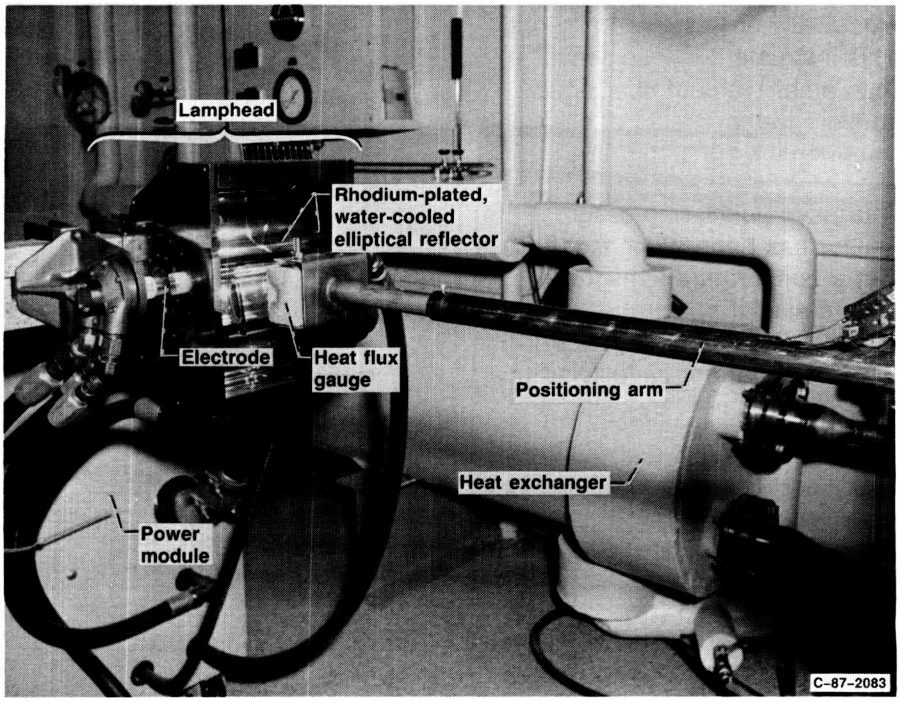
Lewis heat flux gage positioned in calibrator



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Matched-Filter Fiber Optic Pressure Sensor

In conjunction with grant-supported researchers at John Carroll University, Lewis has developed a fiber optic pressure sensor that offers considerable promise for use in aircraft control systems. This instrument uses a novel matched-filter technique to overcome the stability limitations of other types of fiber optic sensors.

The distinctive feature of this instrument is its use of an optical technique to precisely transfer a displacement of the remotely located sensing cavity to the local analyzer. A highly accurate electronic measurement of the pressure-indicating displacement can then be performed in a controlled environment. Cable effects, which frequently hamper remote capacitance measurements, are therefore minimized. Because the sensor is electrically passive, it can be used in high-temperature areas or in other electrically hostile environments. This instrument is less sensitive than other types of fiber optic sensors to the effects of changing the fiber-link components.

A proof-of-principle pressure sensor has been demonstrated, as has a temperature sensor that uses a similar spectral encoding method. Present research is directed at further simplifying this type of instrument by using a passive analyzer.

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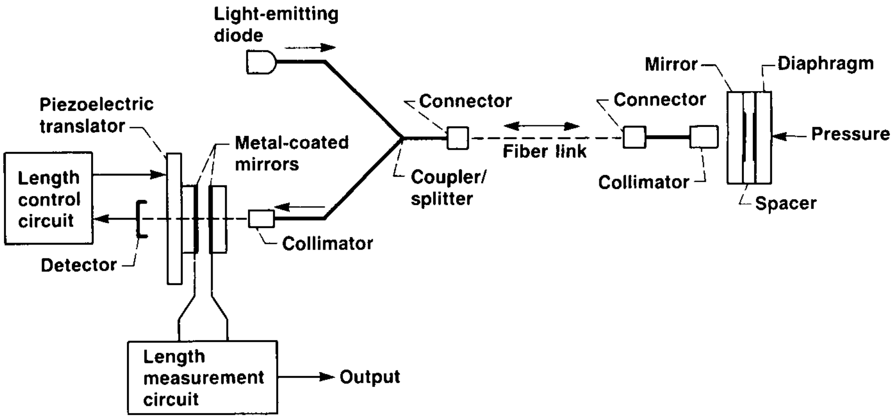

Matched-filter fiber optic pressure sensor

Advanced Sensor Failure Detection for Propulsion Controls

The objective of the Advanced Detection, Isolation, and Accommodation (ADIA) Program is to demonstrate satisfactory engine control system operation after a system sensor has failed. The ADIA program is based on the principle of analytical redundancy. A dynamic model of the engine (and analytical function) as well as the sensed engine variables is used to generate redundant estimates of the sensed variables. These redundant estimates are compared with the sensor outputs. Significant discrepancies indicate a sensor failure.

An ADIA algorithm was developed, by using advanced decision and control theories, to detect, isolate, and accommodate both hard and soft failures over the full engine operating range. Hard sensor failures are large, instantaneous failures that strongly affect system operation. They are therefore easily detected. Soft failures, on the other hand, are small and can occur slowly (such as a drift). They are therefore more difficult to detect. As a result the logic to detect soft failures is more complex than that for hard failures.

The algorithm was successfully implemented with standard microprocessor-based hardware. Computing requirements were met by using three identical processors in a parallel-processing environment. Algorithm programming was significantly simplified by using Fortran and floating-point arithmetic.

A full-scale engine demonstration of the ADIA technology was recently completed in the Lewis Propulsion Systems Laboratory (PSL). In this test high-performance failure detection was demonstrated on an F100 engine.

Failure sizes smaller than possible with any other detection algorithm were demonstrated. The capability to detect multiple and simultaneous sensor failures and excellent post-failure (i.e., accommodation) performance were shown. Good engine steady-state and dynamic performance with single sensor failures was also demonstrated. Finally, the engine was controlled over a wide power range with all of the feedback sensors purposely failed. This test showed the superior accuracy of the dynamic model used in the failure detection algorithm.

This program incorporated technology that was successfully demonstrated in the F100 Multivariable Control Program and tested in the PSL facility in 1979.

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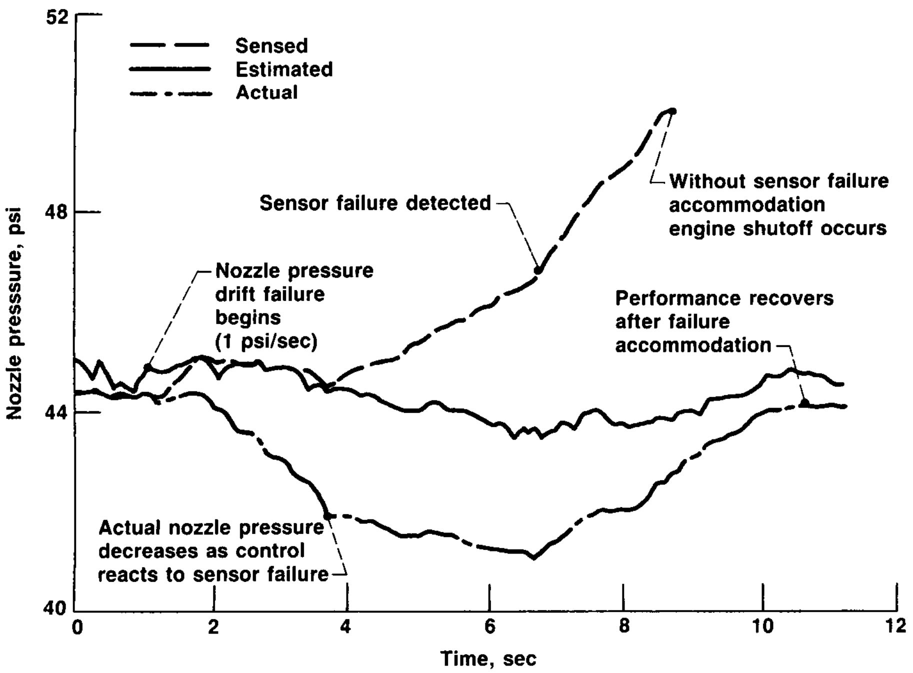

Soft sensor failure accommodation (altitude, 10 000 ft; Mach 1.2; military power)

Internal Fluid Mechanics

Oscillating Convective Flows Caused by G-Jitter

G-jitter (oscillating acceleration) is the primary source of convective disturbances during materials processing in the space shuttle environment. Lewis is seeking to identify the extent and nature of g-jitter's effects in causing fluid flow instabilities and in promoting fluid mixing in bulk fluids and at fluid-fluid interfaces.

Analytical work has been concentrated on defining the stability limits of certain important basic state flows that are generated by g-jitter and on understanding the nature of these instabilities. Basic state flows include oscillating Couette flow (for g-jitter in a bulk fluid), oscillating viscous Kelvin-Helmholtz flow (for g-jitter parallel to an interface), and a motionless fluid with an oscillating pressure field (for g-jitter normal to an interface.) Numerical work has been directed toward simulating and understanding the finite amplitude development and the statistical steady state of these instabilities. A boundary tracking technique has been developed to simulate interfacial perturbations. A spectral approach is currently being developed to study the mixing effects of g-jitter in bulk fluids.

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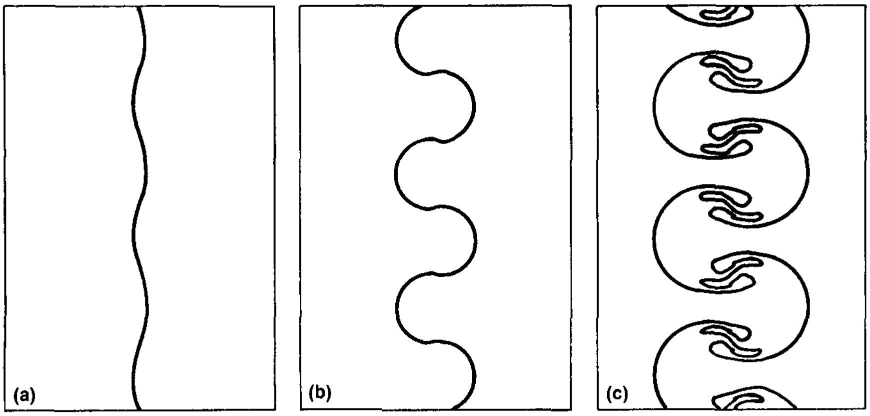
Early evolution of density interface subject to g-jitter for Stokes-Reynolds number of 12: (a) after 1 g-jitter oscillation; (b) after two oscillations; (c) after three oscillations. (The g-jitter is directed horizontally. The interface is initially perturbed from the vertical by a small-amplitude sinusoidal disturbance.)



Rotor-Stator Interaction

The major thrust in the computational analysis of turbomachinery to date has been the steady-state solution for the flow in isolated blade rows using mass-averaged inlet and exit conditions. Unsteady flows differ from the steady solution because of the presence of interacting pressure waves and wakes between blade rows. Rotor-stator interaction research at Lewis seeks to predict these actual complex flow conditions by looking at the time-accurate solution in one stage of a turbomachine.

An in-house quasi-three-dimensional viscous code used to solve for the flow in an isolated turbomachinery blade row was modified to handle equal-pitch rotor-stator interaction computations. The solution procedure has been applied to the first stage turbine rotor of the space shuttle main engine (SSME) fuel turbopump. For this calculation the upstream stator was scaled such that its pitch matched that of the rotor and the pitch-to-chord ratio remained unchanged. A converged periodic solution was obtained after the stator had seen 10 passing rotor blades or 10 pitch rotations of the rotor, which takes about 2.5 hr on the Cray. The analysis is now being applied to a multipassage problem where the stage blade configuration is two upstream stators followed by three rotors. The actual blade geometry of the entire first stage of the SSME fuel turbopump comprises 41 stator blades and 63 rotor blades.

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SSME rotor-stator interaction (pitch rotation, 15.25)

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Composite Grid and Robust Numerical Scheme for Turbine Flow Simulation

Numerical simulation in turbine flows can be made more accurate by improving grid properties (orthogonality, smoothness, and resolution) and by using an efficient and robust numerical scheme. No single grid offers satisfactory grid properties in the entire turbine stator passage or the entire rotor passage because of the large camber, high solidity, and substantial thickness of turbine blades.

A composite grid was generated in an attempt to improve grid quality. This composite grid consists of the C-grid (or O-grid) in the immediate vicinity of the blade and the H-grid in the upstream region and in the middle of the blade passage between the C-grids. It provides good boundary layer resolution around the leading-edge region for a viscous calculation, has orthogonality at the blade surface and slope continuity at the C–H (or O–H) interface, and has flexibility in controlling the mesh distribution in the upstream region without using excessive grid points. This composite grid eliminates the undesirable qualities of a single grid when generated for a typical turbine geometry.

A finite-volume, lower-upper (LU) implicit scheme can be used in solving for the turbine flows on the composite grid. This scheme was demonstrated at Lewis to be robust and efficient in a broad flow regime for standard flow problems and is expected to yield accurate solutions on the improved composite grid for turbine flow problems.

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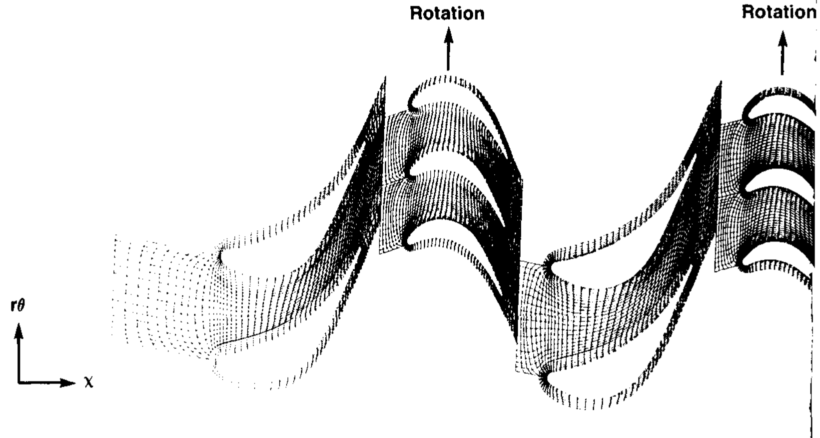

Composite grid for space shuttle main engine fuel-turbopump turbine

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Unsteady Heat Transfer in Rotor Wake Flows

Heat transfer to gas turbine blades is strongly influenced by periodic wake shedding from upstream vanes. The highly unsteady wakes significantly raise blade heat flux levels. Lewis is working to measure the effects of wake passing on turbine-blade heat transfer and to relate these effects to characteristics of the wake-dominated flowfield. The research is being conducted in an annular-flow, open-circuit wind tunnel in which simulated rotor wakes are produced by a rotating spoked wheel. In the initial phase of the research heat transfer measurements have been obtained from the stagnation region of a circular cylinder.

Phase-locked mean and fluctuating characteristics of the wake-dominated flowfield have been measured over a wide range of cylinder Reynolds numbers and wake-passing frequencies by means of hot-wire anemometry. Unsteady heat transfer was recorded simultaneously at several circumferential locations in the cylinder stagnation region by means of thin-film heat flux gages. Analysis of the data revealed a direct relationship between the observed large, unsteady increase in heat flux during wake passing and a corresponding increase in wake-induced flow unsteadiness.

Asymmetric effects of the wake-passing events on the stagnation-region boundary layer were also revealed. The positive wake-induced heat flux excursions were much larger on the windward side (with respect to the wheel rotational direction) of the cylinder. The windward side of the cylinder corresponds to the suction side of a turbine airfoil. This asymmetric heat transfer situation is also reflected in previously obtained steady-state heat transfer coefficient distributions.

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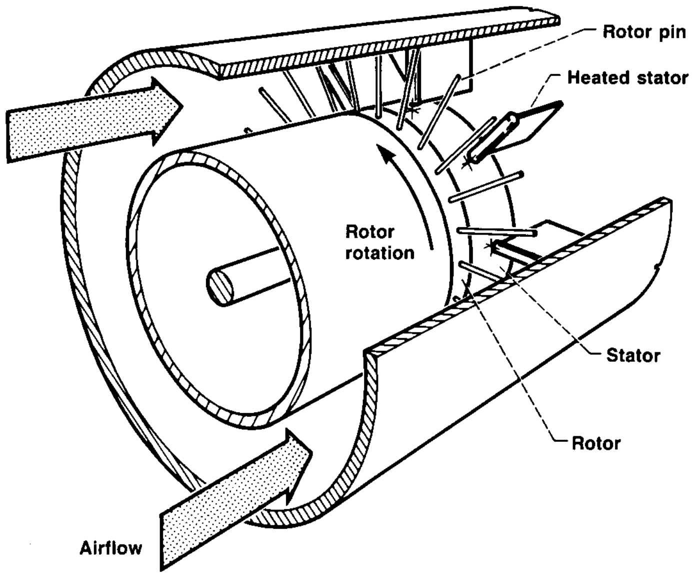

Rotor wake flow test apparatus

Basic Multiphase Flow Research

For the first time in a two-phase fluid flow study of liquid jet atomization in high-velocity gas streams, good agreement was obtained between the measured and theoretically predicted effects of gas flow rate on the characteristic drop size of a spray. This result was achieved by sampling the spray close to the point of initial spray formation and thereby avoiding losses of small droplets from the spray due to their rapid vaporization and dispersion downstream of the atomizer. A scattered-light scanning instrument, which was developed at Lewis and improved in recent studies, was used to measure Sauter mean and volume median diameters as small as 5 μm. Analysis of the data, at a sampling distance of 2.2 cm downstream of the atomizer, showed the Sauter mean diameter to be proportional to the nitrogen gas flow rate raised to the 1.33 power. The exponent 1.33 is the same as that predicted by atomization theory for liquid jet breakup in the acceleration wave regime of atomization. In previous studies an exponent of only 1.2 was obtained when the spray was sampled at a distance of 4.4 cm downstream of the atomizer. This lack of agreement with atomization theory was attributed to the loss of small droplets by vaporization and dispersion.

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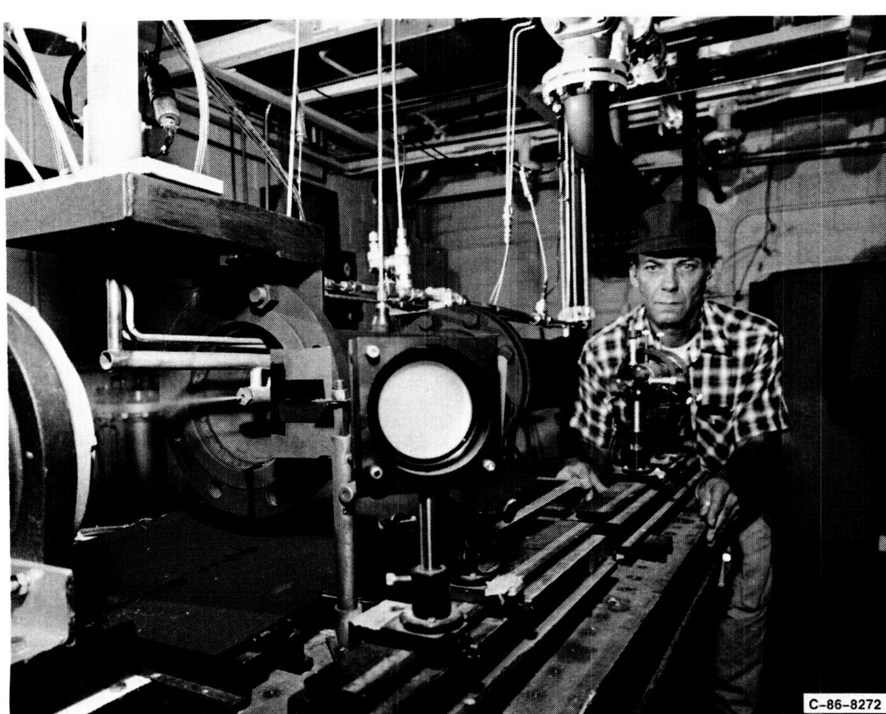

Multiphase flow test apparatus

Propulsion Systems

Ceramic Components for Gas Turbine Engines

To exploit the high-temperature performance potential of the gas turbine engine without using strategic materials or exotic hot-section cooling techniques, Lewis is working to develop a ceramic component technology base. As part of the U.S. Department of Energy's Automotive Gas Turbine Program structural ceramics are being applied to the hot-flow-path components of advanced small gas turbine engines. These engines, which could operate to 2500 °F, may use significantly less fuel then either metal turbine engines or conventional piston engines with emission levels that meet or exceed current and proposed Federal standards.

Technology development contracts are in place with the Allison Gas Turbine Division of General Motors and with the Garrett Turbine Engine Company. Each contract relies on the strong support of the ceramics industry for component development. During the past year considerable improvement in both the dimensional quality and strength of ceramic components has been demonstrated. The first phase of this DOE program was completed in 1987 with the testing of an entire set of ceramic hot-flow-path components in a 2200 °F engine environment. This is the state-of-the-art use temperature for the current generation of ceramic materials.

With continuing DOE support Lewis is entering the second phase of the program, extending the level of ceramic technology to 2500 °F. The project combines extensive analysis, design, fabrication process development, and testing to further improve ceramic component reliability in an engine application.

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Ceramic Components for Low-Heat-Rejection Diesel Engines

Lewis is continuing technology development for advanced low-heat-rejection (LHR) diesel engines under an interagency agreement with the U.S. Department of Energy. In the LHR concept conventional water cooling is eliminated and selected components are insulated to significantly reduce in-cylinder heat loss. This improves engine efficiency, particularly for turbocharged and turbocompounded engines, where energy is recovered from the high-temperature exhaust gases. The high-temperature operation, however, necessitates technological advances in both in-cylinder insulation and tribology.

Thermal barrier coating technology contracts are under way at Caterpillar, Inc., and Cummins Engine Company with the objective of developing plasma-sprayed zirconia insulation systems for use on diesel piston caps and cylinder heads. A significant technology base developed at Lewis for thick (150 mils) plasma-sprayed zirconia insulation on turbine tip seals is being adapted to meet the diesel requirement. The contractors have used finite-element modeling techniques to thermomechanically analyze numerous candidate coating systems applied to the complex curvature of the piston cap. Analysis results indicate that a graded design with cermet layers near the metal substrate has the best probability of survival. Multiaxis robots are being programmed to apply the coating. Completion of the contracts is anticipated in fiscal year 1988 with 100-hr testing of coated components in the contractors' single-cylinder research engines.

Significant tribological problems are present at the interface between the piston ring and the cylinder liner, where insulated operation produces temperatures that exceed the capability of conventional lubricants. Completed analysis of insulated engine operations indicates that temperatures in the ring and liner area may approach 1200 °F. Southwest Research Institute has completed pin-on-disk tests identifying two pairs of advanced materials that can be run unlubricated at friction coefficients competitive with those of current liquid-lubricated systems. Single-cylinder engine testing is planned to confirm the unlubricated friction levels with full-scale components.

Detroit Diesel Allison is investigating an alternative approach to high-temperature ring and liner lubrication (i.e., the use of high-temperature solid- or vapor-phase lubricants in the ring and liner area).

The higher combustion surface temperatures achieved in LHR diesel engines also influence the gaseous and particulate exhaust emissions. Southwest Research Institute is currently using an insulated, single-cylinder research engine to evaluate these emissions over a range of operating conditions.

In an effort to better understand LHR thermodynamics, Integral Technologies, Inc., has completed an extensive modeling analysis of the heat transfer and thermal processes in insulated engines. Testing to validate the model parameters is under way in an insulated, single-cylinder research engine built at Purdue University. The test instrumentation includes prototype total heat flux sensors with sputtered thin-film thermocouples fabricated at NASA Lewis. The unique heat flux instrumentation has operated successfully in the engine at indicated mean surface temperatures to 1250 °F.

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Supersonic Throughflow Fan

Engine cycle studies have indicated large potential advantages for a supersonic throughflow fan (STF) in advanced propulsion systems. These advantages are shorter, lighter weight, more efficient completely supersonic inlets and the ability to achieve the desired high overall fan pressure ratio in a simpler, lighter weight single stage. Lewis has therefore embarked on a program to experimentally investigate the STF concept. A supersonic throughflow fan has been designed by using the latest advanced computational codes. An existing axisymmetric compressor design code was modified to accommodate supersonic throughflow velocities and was used to generate the blade shapes. A quasi-three-dimensional, thin-shear-layer Navier-Stokes code was used to calculate the internal flowfield within the rotor and stator blade passages. The numerical results show only weak shock waves existing within the blade passages. When the blade loading is properly controlled, the expansion waves off the suction surface tend to cancel the compression shock waves from the pressure surface. The resulting blade shape also minimizes the pressure gradients near the trailing edge and thus prevents strong expansion or compression waves from forming there. Off-design calculations have been made to assess the startup problem and to predict off-design performance with supersonic throughflow velocities.

An existing multistage compressor facility is being modified to test the recently designed STF. The facility modifications include the incorporation of a variable-inlet nozzle to establish the supersonic flow at the fan inlet and a variable-geometry diffuser downstream of the fan to diffuse the flow to subsonic conditions.

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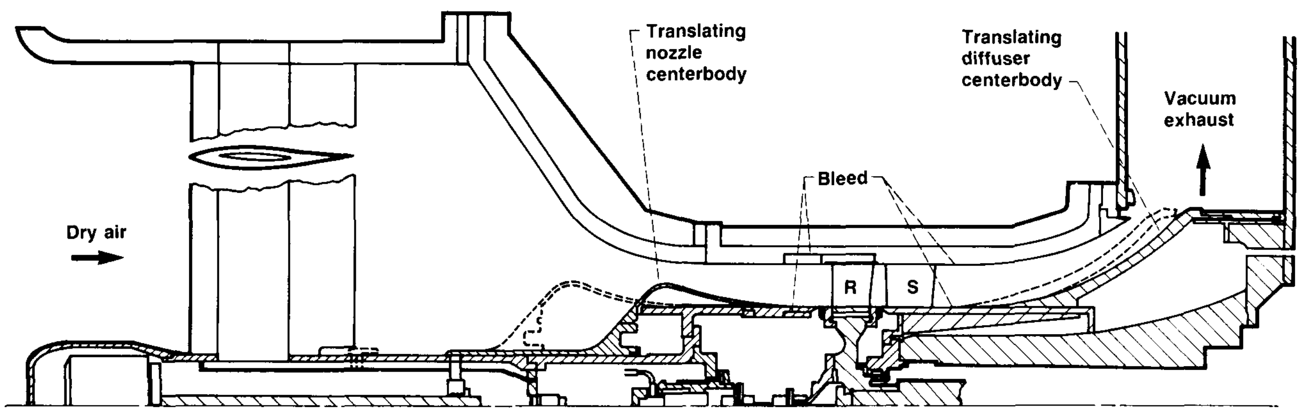
Supersonic throughflow fan test package (pressure ratio, 2.45; inlet axial Mach number, 2; rotor tip speed, 1500 ft/sec; tip diameter, 20 in.)



Model Tests of Advanced Counter-rotation Propeller

A series of four 2-ft-diameter models of the counterrotation unducted fan were evaluated in the Lewis 9- by 15-Foot Wind Tunnel. Noise at community conditions (e.g., takeoff), reverse thrust performance, and aero-elastic behavior were measured. Parameters investigated included equal and unequal blade numbers, three rotor-rotor spacings, and a reduced-diameter aft row. In addition, installation effects due to operation with the propeller axis at an angle of attack to the incoming flow and the presence of an upstream pylon were investigated.

Continuously traversing microphones were used to measure sideline and circumferential directivities of the propeller tones. Although tones associated with either rotor alone peaked near the plane of rotation, the directivity of the interaction tones (due to upstream rotor wakes and vortices interacting with the downstream rotor) was flat, indicating a longer duration of the flyover noise at takeoff. Spacing strongly affected the interaction tones while rotor-alone tones remained unchanged. An angle of attack of 16° increased the fundamental tones by more than 10 dB.

Reverse thrust was measured for several configurations including blades rotated through both flat pitch and feather and one blade row feathered and the other in reverse. Scaled results indicated that reverse thrusts of 25 to 45 percent of takeoff thrust could be attained, depending on aircraft Mach number. These values equal or exceed comparable reverse thrusts produced by current turbofans.

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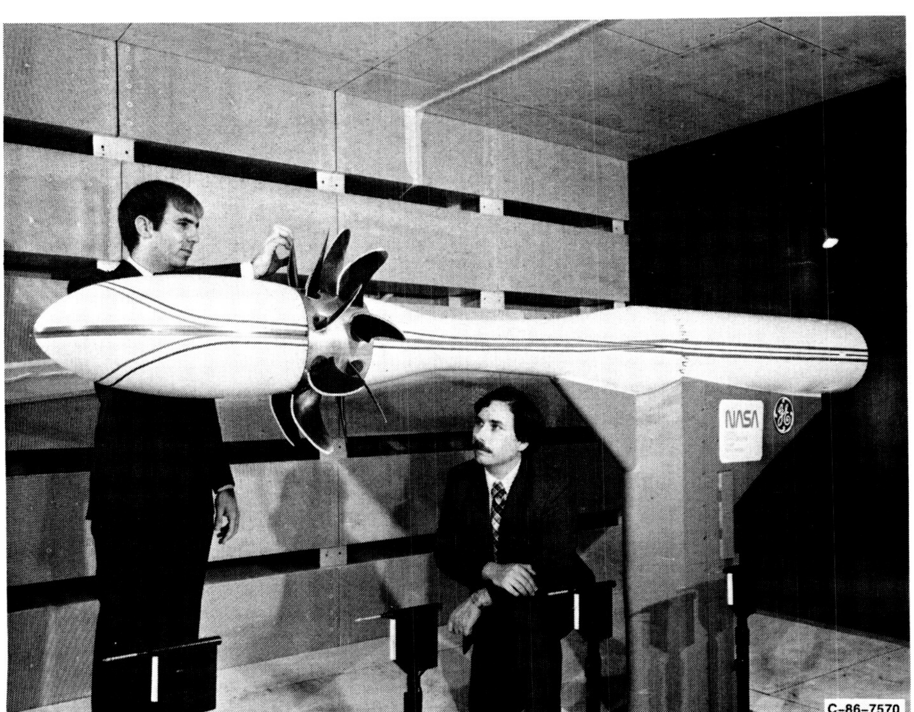

Counterrotation propeller on unducted fan model in wind tunnel

Flight Testing of Large-Scale Propfan

As part of its program to improve the fuel efficiency of high-speed subsonic aircraft, Lewis is now flight testing a 9-ft-diameter advanced turboprop on a modified Gulfstream G–II testbed airplane. Derivatives of this advanced propeller design may be used in the 1990's to power commercial airliners with significant reductions in fuel consumption and no compromise in cruise speed. The test article, a single-rotation propfan consisting of a row of eight thin, swept, highly loaded blades mounted on an area-ruled spinner, was designed and manufactured by Hamilton Standard Division of United Technologies, Inc., under a NASA contract. The testbed airplane, with the propfan powerplant installed on the left wing, was modified and is being tested by Lockheed-Georgia Co. under another NASA contract. The purpose of this flight testing is to verify the structural integrity and characterize the acoustics of the propfan over a wide range of actual flight conditions.

The airplane modifications and propfan powerplant and nacelle installation were completed in February. Airworthiness envelope expansion flights with the propfan were completed in early June. There was no evidence of propfan or airplane flutter up to the maximum dynamic pressure dive speed condition at Mach 0.89/28,000 ft. Propfan structural integrity envelope clearance flights were performed over low-speed and high-speed conditions to Mach 0.85 at 40,000-ft altitude with the propfan operating at maximum continuous power conditions. Propfan blade stresses, as predicted, were much lower than allowable limits for the nominal nacelle tilt. In subsequent flight testing, which began in July, propfan structural and acoustic response to a variety of air inflow angles was investigated by varying nacelle tilt relative to the wing at different flight and propfan operating conditions. Propfan source noise data were acquired from external fuselage and wing surface microphones as well as from microphones located on a wing-mounted boom outboard of the propfan. Extensive baseline internal cabin acoustic data were also acquired for a bare-wall cabin to identify treatment requirements. Flight testing of an advanced cabin acoustic treatment will begin in early 1988.

Data acquired in these tests will be used to verify propfan aeroelastic and aeroacoustic modeling codes being developed by NASA and industry. The single-rotation forced response and acoustic data will lead to a clearer understanding of the similar but more complex interactions of counterrotation designs. These basic modeling and design codes when fully developed will be applicable to both types of configurations. Many of the design features verified in this test of the single-rotation system (e.g., the thin, swept blade shape with spar and shell construction, the pitch-change controls, and the disk retention design) have direct application to the Hamilton Standard counterrotation propfan being flight tested on the Douglas MD–80.

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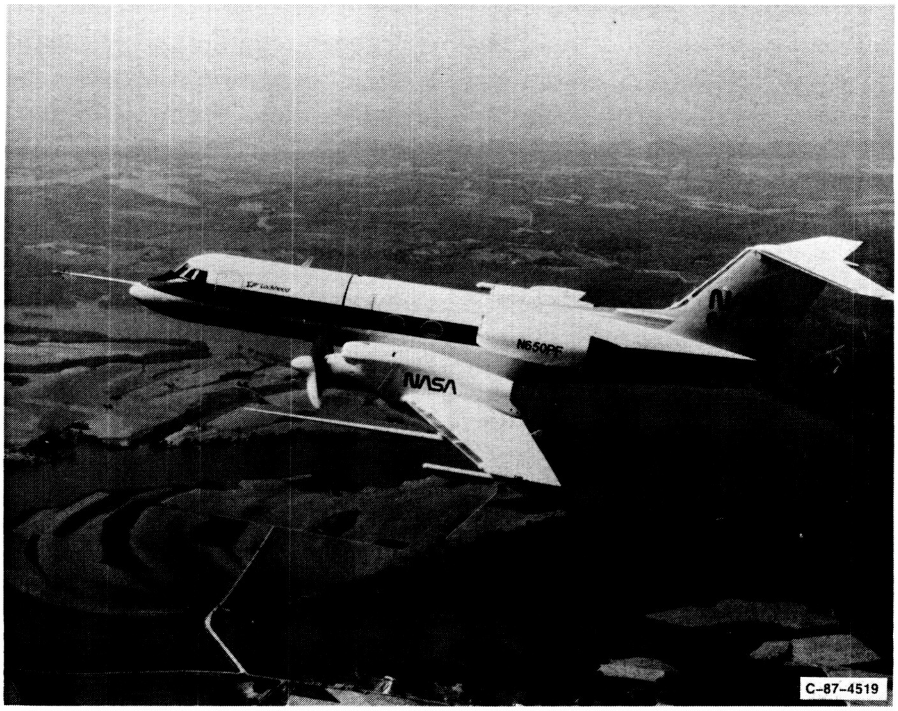

9-ft-diameter propfan on Gulfstream G–II aircraft

Flight Testing of Unducted Fan Engine

The Lewis-funded unducted fan is unique in that its thin, swept propeller blades are directly driven by the multistage power turbine without the need for gearbox speed reduction. The counterrotation power turbine is mechanically uncoupled from the upstream F404 turbofan engine, which supplies the necessary hot gas. This and other conventionally geared counterrotation systems have smaller blade diameters and lower rotational, or "swirl," exit energy losses than single-rotation propellers.

The General Electric Company has completed proof-of-concept flight tests of a 25,000-lb-class unducted fan engine mounted on a Boeing 727.

At its flight test facility in Mojave, California, GE completed 25 flights (~41 hr of test time) at speeds to Mach 0.84 at 36,000 ft. The unducted fan engine used about 50 percent less fuel than the JT8D turbofan engine it replaced on the 727. Blade stresses tended to be higher than desired, although within limits, until a new low-flex, forward-stage prop design was evaluated during the final 3½ hr of the 727 flight test effort. The engine-order blade response was reduced by a factor of 3 or more.

During the 727 flight test program 16 far-field acoustic data points were acquired at altitudes above 21,000 ft with the Lewis Learjet chase plane. Ground measurements of enroute noise at several altitudes as well as low-altitude airport and community flyover noise data were also obtained for the Federal Aviation Administration. Interior cabin noise was recorded by Boeing for three configurations: a standard cabin, a standard cabin with a leaded plastic aft bulkhead curtain, and a cabin with a floating plywood floor. Data from these tests are still being analyzed.

In addition to the flight tests the unducted fan also successfully demonstrated its capability to transition from takeoff to reverse thrust at 100 knots in subsequent ground testing with the 727.

After 727 testing was completed in February the proof-of-concept engine was refurbished and installed on a new pylon on the opposite side of a Douglas Aircraft Company MD–80 so that the performance of the same unducted fan engine could be compared on two different aircraft. Concurrent with this flight testing in June and July was a 30-hr ground test of a new 10-by-8 blade unducted fan prop configuration at GE's Peebles, Ohio, test facility. The 10-by-8 configuration was designed as an acoustic improvement over the original 8-by-8 configuration. The unequal number of blades on the fore and aft rotors of the new design reduces the potential of acoustic reinforcement between the two rows. Flight testing of this new configuration on the MD–80 began in August for completion late this year. Extensive blade stress, engine condition, performance, and cabin acoustic measurements were made to establish the readiness of the unducted fan engine for commercial development.

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GE unducted fan propulsion system on Douglas MD–80

Liner Cooling Research

Research relating to the evolution of fuel-efficient small gas turbine engines capable of meeting future commercial and military aviation needs is currently under way at Lewis. Higher gas turbine engine efficiency and lower specific fuel consumption can be realized by increasing cycle pressure ratios and turbine inlet temperature. However, combustors operating at those conditions require larger amounts of cooling. At the same time the air has less heat sink capability because of higher combustor inlet temperatures resulting from increased cycle pressure or regenerative cycle operation. Advanced cooling techniques must be incorporated in the combustor liner to achieve the potential for implementing advanced cycles.

Lewis is conducting a component research program for advanced small gas turbine engines. As part of this research different advanced liner wall cooling techniques were investigated in the same reverse-flow combustor geometry. The liners were compared with a splash-film-cooled (SF) baseline combustor. Combustors incorporating counterflow-film-cooled (CFFC) liner panels, transpiration-cooled liner walls (TRANS), and compliant metal/ceramic (CMC) walls were evaluated at a simulated pressure ratio of 16 and fuel-air ratios to 0.034. The CFFC and TRANS designs used 40 to 50 percent less coolant than the SF design. The CMC walls required only back-side convective cooling and reduced the coolant flow by 80 percent. The three advanced liners studied had similar reductions in liner temperature. The CMC liner demonstrated good short-term durability to outlet temperatures of 2630 °F—at least 300 deg F hotter than current practice. Lewis plans to evaluate the CMC concept at 3000 °F with minimal cooling applied to the compliant substrate.

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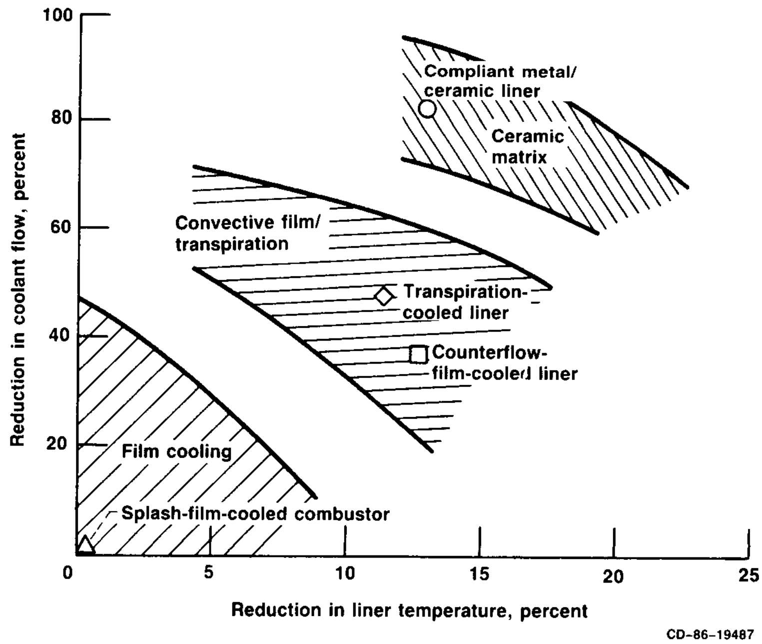

Comparison of liner cooling effectiveness

Centrifugal Compressor Scaling

A problem confronting the designers of small compressors is the reduction in efficiency that occurs as flow size is reduced. Several factors—Reynolds number, surface roughness, tip clearance, blade thickness, fillet radius, and secondary flow—are known to contribute to the efficiency loss, but the variation in loss that results from a change in each factor is not well known. Controlled experiments are needed to develop mathematical models that can be used to predict and minimize these losses. The joint NASA Lewis and U.S. Army Centrifugal Compressor Scaling Program has provided a data base for model development and code verification by determining the loss variation associated with each factor.

A 25-lb/sec centrifugal compressor was directly scaled down to a 10-lb/sec flow size. It was also scaled down to 2 lb/sec, but the directly scaled blade thickness had to be increased to maintain a structurally sound compressor. To maintain a link to the original compressor, the 2-lb/sec compressor was then directly scaled up to the 10-lb/sec size. The efficiency loss caused by the increased blade thickness was determined by comparing the performance of the two 10-lb/sec compressors.

Last year, test results were reported for the directly scaled 2-lb/sec and 10-lb/sec compressors operating over a range of Reynolds numbers. When operated at the same Reynolds number, the two compressors performed at the same level of efficiency.

During 1986 the two 10-lb/sec compressors with different blade thicknesses were tested over a range of blade tip clearances and impeller Reynolds numbers. At design values of speed and tip clearance increasing the blade thickness lowered the compressor efficiency by 1.5 to 2.2 points over the range of Reynolds numbers tested. The 10-lb/sec thin-blade compressor was tested with a thin and a thick shroud. The data showed that shroud thickness can influence the correlation of efficiency loss and Reynolds number. This is attributed to stage interheating caused by heat conduction along the shroud. These data provide a basis for validating advanced mathematical codes.

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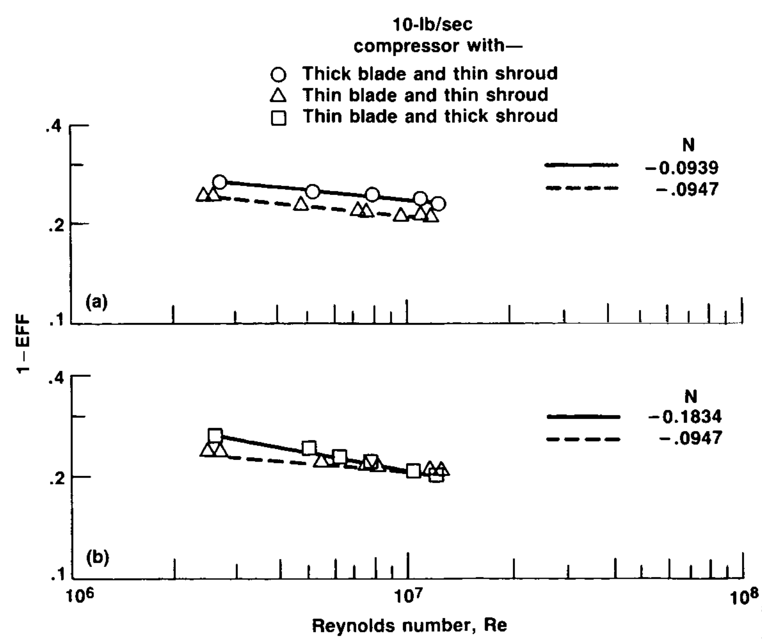

Efficiency loss at design speed: (a) with Reynolds number and blade thickness and (b) with Reynolds number and shroud thickness. $(1 - EFF)/(1 - EFF)_{ref} = [Re/(Re)_{ref}]^N$.

Contingency Power for Turbine Engines by Water Injection Into Turbine Cooling Air

Because of one-engine-inoperative requirements together with hot-gas reingestion and hot-day, high-altitude takeoff situations, power augmentation for multiengine rotorcraft has always been of critical interest. However, overheating turbine engines to significantly augment power will substantially shorten engine life unless a method of limiting turbine blade thermal and mechanical stresses is found. A joint NASA Lewis and U.S. Army effort was conducted to research the feasibility of cooling the turbine cooling air by using the latent heat of vaporization of water injected into it. The cooler, heavier cooling air would then be more effective in cooling the turbine blades, thus allowing more fuel to be burned by the engine and therefore higher power output. The research effort addressed basic heat transfer, analytical feasibility and design, and experimental demonstration of the concept.

The program was successfully completed this year. A unique system for injecting and evaporating water in the turbine cooling air was designed, fabricated, and tested in a T700 turboshaft engine. The system increased the engine's power output by 17 percent over its nominal maximum power capability. This corresponded to a turbine temperature increase of 300 deg F at a constant turbine rotor blade metal temperature. Furthermore introducing water into the test engine did not damage it. The success of this approach to power augmentation is believed to provide a new approach to contingency power for new rotorcraft and other powered-lift aircraft.

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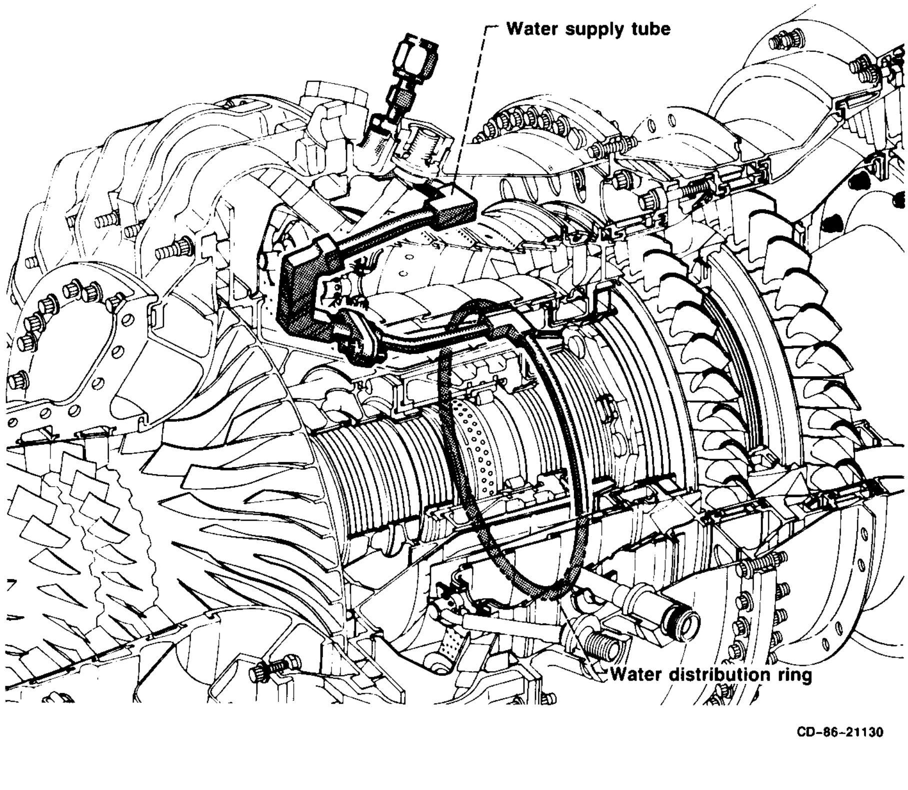

Water injection system installed in T700 engine

Procedure for Designing Cooled Radial Turbines

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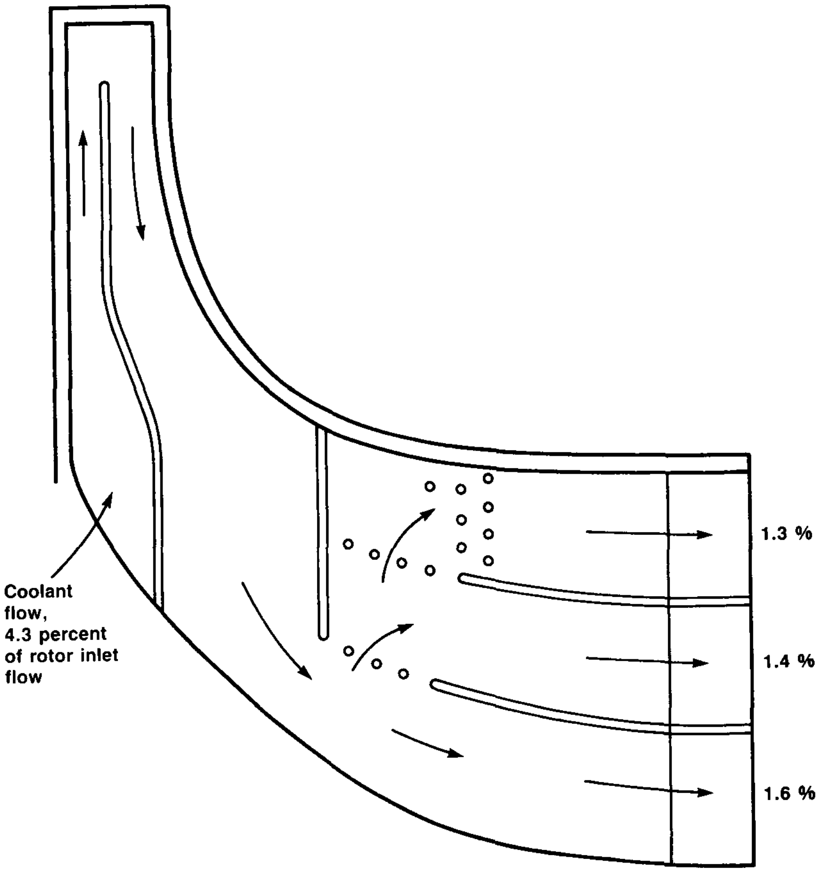
All current aircraft engines use axial turbines. The radial turbine has yet to be used in spite of its benefits. These benefits include reduced overall engine complexity, length, and weight; higher engine efficiency; and lower tip-clearance-related leakage. Although uncooled radial turbines are used in auxiliary power units, material constraints limit their inlet temperatures and thus prevent their use in aircraft engines. Aircraft engines require higher turbine inlet temperatures for lower specific fuel consumption and higher output power. Cooling air must be introduced to allow the radial turbine to operate at these higher temperatures, using present material temperature limits.

Up to this point the technology to successfully design and fabricate a cooled radial turbine has not been available. Lewis has developed a new design procedure applicable to these turbines. The procedure combines existing aerodynamic, finite-element heat transfer and finite-element structural analysis codes to predict the turbine temperature and stress distribution. The codes were applied for the first time to a cooled radial turbine that will be tested in-house. The procedure will be verified by measuring temperatures and pressures on the rotating turbine rotor in a test with both main-stream and cooling air present. Future work will focus on generalizing the procedure so that different internal coolant passage geometries can be analyzed.

Cooled radial turbine



Mach 5 Cruise Aircraft

In a joint study NASA and industry have identified an "over-under" turbojet plus ramjet as a viable propulsion system for a Mach 5 cruise aircraft. This propulsion system includes a variable-geometry, split-flow inlet and nozzle to provide airflow to the dual-flow engine system, with the turbojet being shut down at Mach numbers greater than 3.

An experimental test program on a two-dimensional inlet that represents the ramjet-only part of flight (Mach 3 to 5) is planned for the Lewis 10- by 10-Foot Supersonic Wind Tunnel (10 x 10 SWT) during 1988. This large-scale inlet incorporates a variable-geometry ramp system and remotely variable plate systems for the main and bleed flows. The model has been extensively instrumented to provide computational fluid dynamics code validation data in addition to inlet performance information.

Supporting research studies for the 10 x 10 SWT inlet test program include flowfield prediction with a three-dimensional viscous analytical code (PEPSIS) and small-scale inlet testing in the Lewis 1- by 1-Foot Supersonic Wind Tunnel (1 x 1 SWT). The analytical code results have indicated a significant boundary layer flow migration on the inlet sidewalls, from the ramp toward the inlet cowl. This low-energy boundary layer is captured by the inlet and results in a large separated flow region in the corner of the cowl, just downstream of the cowl lip. Since the separation occurs in the internal contracting section of the inlet, an unstart will occur unless some system, such as bleed, is employed to reduce the separation. As a result of the three-dimensional analysis additional bleed was added to the inlet sidewalls and to the inlet cowl.

A small-scale inlet has been tested in the 1 x 1 SWT to verify the flow migration predicted by the analytical code. This model duplicated the external compression system and was opened to a divergent passage downstream of the inlet shoulder to aid in starting. The sidewall flow migration was verified. Since the Lewis 10 x 10 SWT has a maximum Mach number of 3.5, the inlet model will be located under an expansion plate to accelerate the flow to about Mach 4.1 (the Mach number on the first inlet ramp for the flight condition of Mach 5). The small-scale model was also used in the 1 x 1 SWT to verify the use of the accelerator plate to provide the higher Mach test condition. Additional testing in the 1 x 1 SWT to study cutback sidewalls, a reduced blockage expansion plate, and bleed patterns to control high-pressure gradient–boundary layer interactions in the inlet model have been completed.

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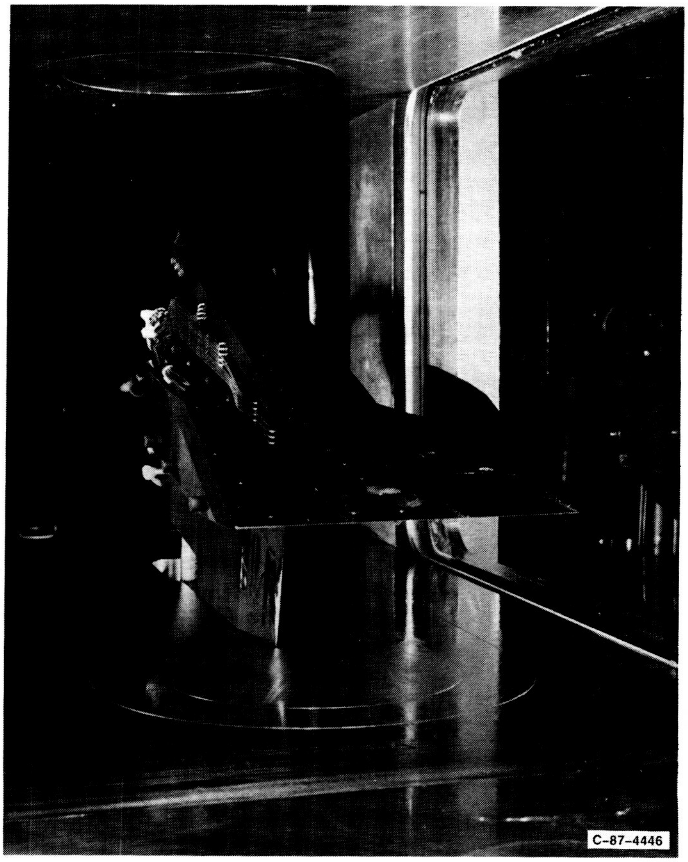
Small-scale Mach 5 inlet model (design Mach number, 2 to 5; maximum dynamic pressure, 15 psi; maximum dynamic temperature, 100 °F)



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Dynamic Load Effect on Spur Gear Pitting Fatigue Life

Accurate prediction of pitting fatigue life is an essential step in improving gear design. Pitting is the removal of small surface particles from gear teeth through repeated application of high contact stress. Previous work at Lewis in calculating pitting fatigue life and reliability for gears assumed a static contact load between the mating gear teeth. A large safety margin was required to compensate for the unknown effects of dynamic loading. Improvements in design are now possible because both dynamic load and its effect on gear life and reliability are better understood.

TELSGE, a Lewis computer program for predicting gear dynamic load (available from COSMIC as LEW–13528), has been modified to include an improved gear tooth stiffness model, a load-stiffness iteration scheme, and a pitting fatigue life analysis prediction for low-contact-ratio spur gears. The new program can predict gear tooth dynamic loads, critical speeds, and gear mesh life.

The computer program was used in a parametric study to investigate the effects of rotating speed and gear mesh contact ratio on pitting fatigue life. The results of this analysis will allow designers to extend gear life, to avoid unfavorable operating conditions, and to more accurately forecast gear life.

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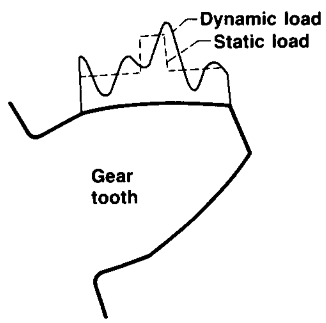
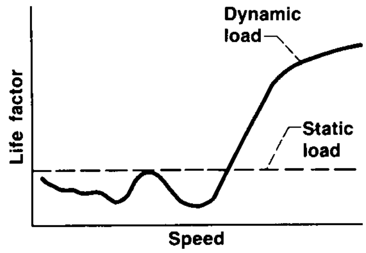


Location of gear tooth loads



Effect of speed on gear tooth life

Design and Evaluation of High-Contact-Ratio Gearing

High-contact-ratio (HCR) gears can improve the performance (life, reliability, and power-weight ratio) of an aircraft transmission. The contact ratio of gears is defined as the average number of teeth in contact. Standard (low contact ratio) gears have a contact ratio of about 1.6. HCR gears have contact ratios greater than 2.0; that is, they always have two or more tooth pairs in contact. This results in lower individual tooth loading.

High-contact-ratio gear teeth are inherently weaker than standard gear teeth because of their longer and more slender shape. Simultaneous tooth contacts tend to make HCR gears more sensitive to tooth spacing errors and profile modifications. Because of these limitations HCR gears require careful and accurate design and manufacture. The Lewis gear dynamic load computer program GRDYNSNG (available from COSMIC as LEW-14099) was found to be essential for establishing a viable design for HCR gears.

Sikorsky Aircraft Division of United Technologies, Inc., under contract to Lewis, performed a design analysis of HCR spur gears using computer program GRDYNSNG. Batches of both standard and HCR gears were fabricated and tested to determine their relative fatigue lives. The HCR gears were found to have two times the life of the low-contact-ratio gears. The scuffing/scoring load capacity of the HCR gears was slightly higher than that of the standard gears.

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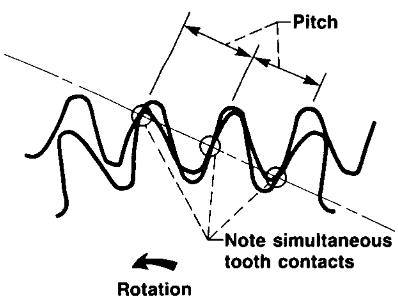
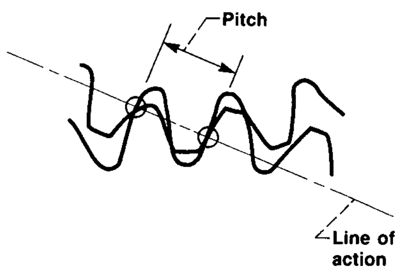


High-contact-ratio gears



Standard gears

Aeropropulsion Facilities and Experiments

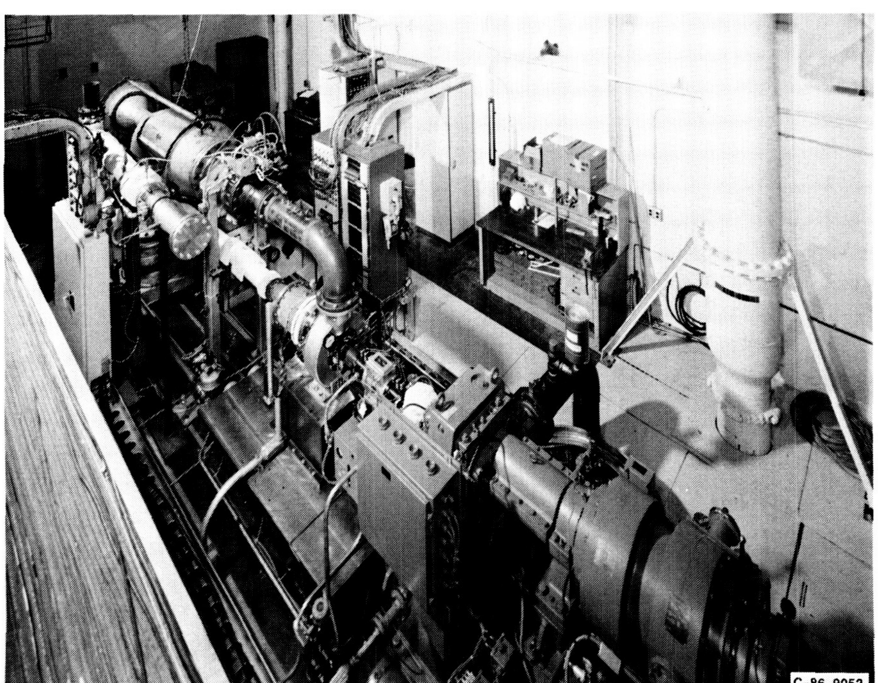
New Small Turbine Facility to Advance Gas Turbine Engine Technology

The improved component efficiencies required in advanced small gas turbine engines dictate the need for modern, versatile test facilities capable of providing high-quality test data. The Lewis Small Warm Turbine Facility meets this need with a number of unique capabilities.

Improved turbine cooling is equal in importance to high aerodynamic performance for small advanced turbines. The new facility can simulate engine levels of primary-coolant temperature ratio, which is a key parameter in assessing the aerodynamic and thermodynamic effectiveness of turbine cooling. Rotor metal temperatures are measured with a unique rotating data package—a special instrumentation package allowing as many as 36 temperature and pressure measurements in the rotating blades. Detailed aerodynamic measurements are obtained with the rotating data package and then later with laser measurements.

The facility was designed for turbine speeds to 60 000 rpm. It can accommodate both axial and radial turbine configurations (actual or scaled test hardware). The research turbine drives a dry-gap-eddy-current, 1250-hp dynamometer through a speed-reducing gearbox and an in-line torquemeter. Pressurized air to 125 psig and temperatures to 800 °F are supplied to the turbine. The inlet air is heated either by an electrical heater (to 300 °F) or by burning natural gas in a modified jet engine combustor (to 800 °F). A second air supply system provides chilled air to simulate the cooling flows in cooled high-temperature turbines. The turbine exhaust is discharged to either atmospheric or altitude exhaust. The uniqueness of this test facility will greatly enhance Lewis' small turbomachinery test capability.

Small Warm Turbine Facility



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Full-Scale Testing of Supersonic Short-Takeoff, Vertical-Landing Aircraft Components

The goal to develop a supersonic short-takeoff, vertical-landing (STOVL) aircraft in the next few years created a need for a facility in which the capabilities of full-scale components that use advanced propulsion lift concepts could be demonstrated. It is also desirable that these components be combined with an appropriate engine or ultimately a full-scale STOVL aircraft for testing of a fully integrated system. Accurate thrust measurement along all three axes is a prime requirement for this facility.

The Powered Lift Facility (PLF) was designed and built to satisfy these requirements. PLF is a six-component thrust frame capable of measuring forces in the vertical, side horizontal, and axial directions. The triangular thrust frame sits 15 ft above ground so that air recirculation and ground effects do not affect the balance measurements. Forty- or 125-psig combustion air is available to simulate the engine or fan exhaust air used to power the various propulsion lift concepts. The combustion air can be heated to 300 °F by means of a vitiated heater in a parallel pipeline. The hot air is blended with cooler air to give the desired air temperature at the test hardware. The PLF's hydraulic thrust calibration system allows the operator to apply a full range of loads in all component directions. The calibration system greatly enhances the credibility of the thrust measurements.

To date, an ejector duct–plenum assembly and a full-scale, single-sided ejector have been tested. All hardware was provided by DeHavilland Aircraft of Canada. The duct–plenum test consisted of flow and pressure drop measurement only, and the ejector was evaluated for thrust augmentation capabilities. All testing was steady state. Thrust data were as predicted and very repeatable. Only axial loads were of interest, and loads to 4200 lb were recorded. In the near future a calibration nozzle will be tested to evaluate the accuracy of the thrust frame, and General Dynamics ejector hardware will be evaluated for flow characteristics and thrust augmentation. There are also plans to test an engine-ejector configuration, controls technology for the engine-ejector, and ultimately a full-scale STOVL aircraft. Tests at PLF will strongly influence the type of propulsion lift device chosen for a STOVL aircraft, and they will also play a major role in the overall development of these aircraft.

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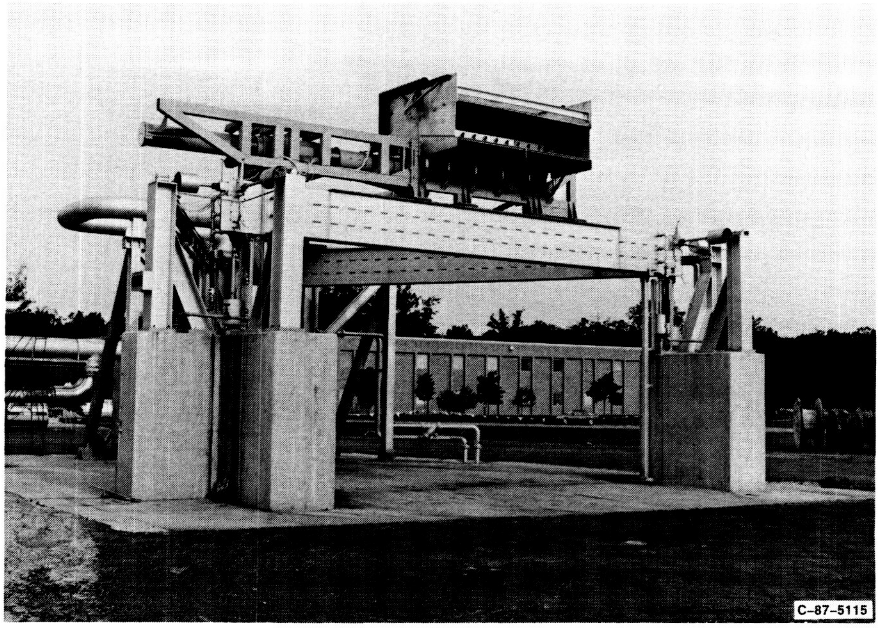
DeHavilland ejector on Powered Lift Facility



Renovation of Icing Research Tunnel Control Room

The Lewis Icing Research Tunnel (IRT), built in 1942, is used to duplicate conditions faced by aircraft flying through icing clouds. Research programs involve testing of civilian and military aircraft components in search of new and improved anti-icing technology and ice protection systems. To keep up with its heavy workload and to expand its capabilities, the IRT has recently undergone a $3.6 million renovation, including the installation of a new control room. The control room modification includes a state-of-the-art microprocessor-based distributed control system manufactured by the Westinghouse Corporation. The WDPF (Westinghouse Distributed Process Family) system allows the operators to fully monitor and control the facility through interactive colorgraphic cathode-ray-tube stations. Automatic following of trends and logging of facility operating parameters is available, as well as a digital closed-loop control system. An interface to operate the damper control valves in the nearby Refrigeration Building is also included.

The WDPF system consists of an engineer's console, an operator's console, two color printers, and three dual digital processing units (DPU's). Eight automatic/manual stations in the Refrigeration Building are interfaced to the DPU's so that they may be controlled locally (at the Refrigeration Building) or remotely (from the IRT control room). All systems are backed up by a dual data highway and dual DPU's. The control system has bumpless transfer from manual to automatic and back and has easily changeable tuning conditions for control loop process points. The tunnel is being calibrated for icing uniformity.

When the IRT starts up again later this year, it will be one of the busiest wind tunnels as NASA. Approximately 70 percent of the work is from aircraft manufacturers, the military, and others outside NASA, and 30 percent of the work is NASA related.

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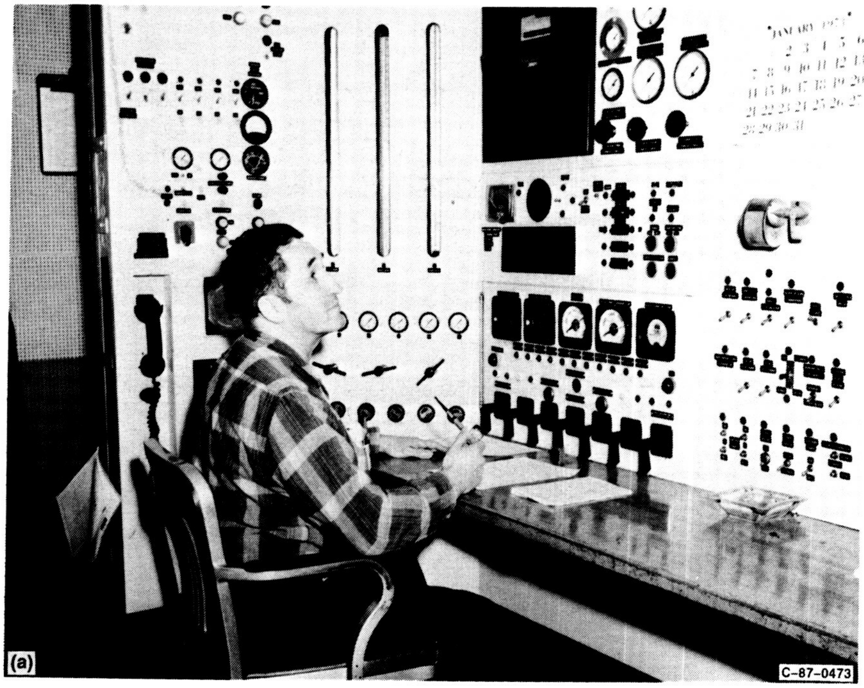

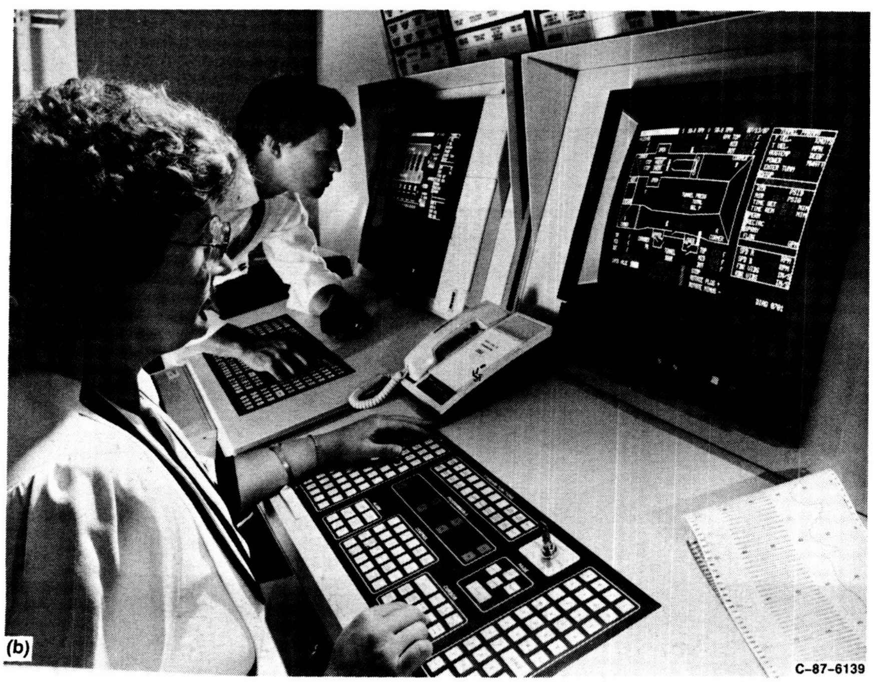

Icing Research Tunnel control room:
(a) before modification; (b) after modification

Materials

Molten Salt Corrosion of Ceramics

Silicon-based ceramics show great promise for numerous high-temperature applications—both as monolithic and fiber-reinforced composite bodies. In applications such as heat engines and heat exchangers these materials would be exposed to corrosive conditions. Previous experience has shown that sodium, in the form of sodium sulfate, is the primary corrosive agent.

Silicon-based ceramics rely on a thin film of SiO_2 for environmental protection. Sodium sulfate can react with this film to form liquid sodium silicate. The liquid silicate is not protective and the silicon-based ceramic is subject to severe attack—grain boundary attack and large crater-like pits in the case of SiC. The pits usually correlate with gas bubbles released by the corrosion reactions. The gas bubbles *expose fresh surfaces of SiC for* extensive attack.

This surface attack can be quite detrimental to ceramics, whose strength shows a strong dependence on surface finish. With SiC ceramics room-temperature strength was decreased by 30 to 50 percent. Extensive fractography clearly showed the corrosion pits to be the sources of failure. The corrosion pit size correlated with the strength of the material as predicted from fracture mechanics.

As silicon-based ceramics find more high-temperature applications, it is important to consider these findings and take appropriate steps to minimize the effect of sodium-induced corrosion.

The paper that reported this work was written by James L. Smialek and Nathan S. Jacobson and was selected as the Lewis Distinguished Paper for 1987.

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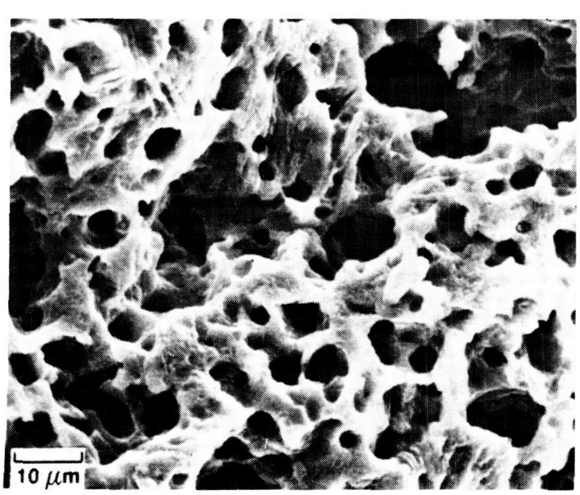
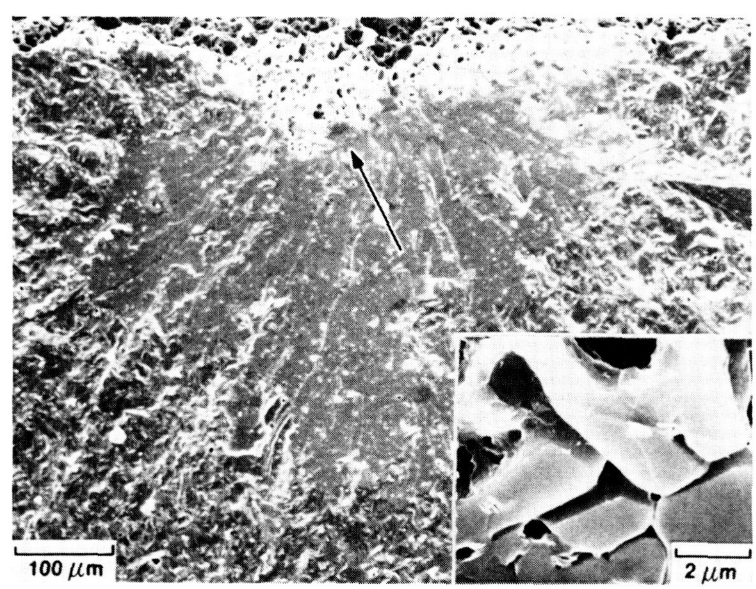
SiC surface after scale dissolution



Corrosion pit as fracture source



Simulation of Fluid Flows During Growth of Organic Crystals in Microgravity

Several counterdiffusion crystal growth experiments have been conducted in space. Improvements in crystal size and quality have been attributed to reduced natural convection in the microgravity environment. One series of experiments called DMOS (diffusive mixing of organic solutions) was designed and conducted by researchers at the 3M Corporation and flown by NASA on the space shuttle. Since only limited information about the mixing process is available from the space experiments, Lewis conducted a series of ground-based experiments in collaboration with the 3M Company and the Marshall Space Flight Center to further investigate the fluid flow within the DMOS crystal growth cell. Solutions with density differences of 10^{-7} to 10^{-4} g/cm^3 were used to simulate microgravity conditions. The small density differences were obtained by mixing D_2O (heavy water) and H_2O. Methylene blue dye was used to provide flow visualization. The extent of mixing was measured photometrically by using the 662-nm absorbence peak of the dye. Results indicate that extensive mixing by natural convection can occur even under microgravity conditions. This is qualitatively consistent with the results of a simple scaling analysis. Quantitative results are in close agreement with ongoing computational modeling analysis.

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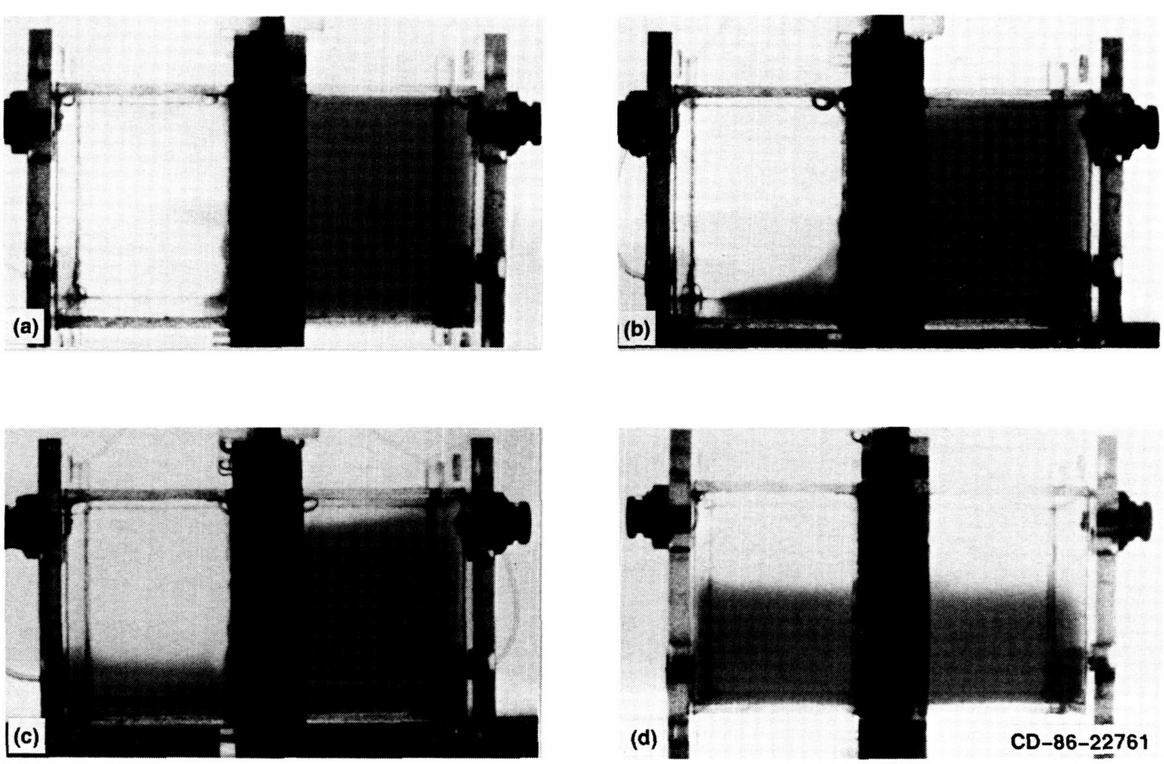
DMOS flow visualization experiment (mixing time, 1 hr; density difference: (a) 10^{-7} g/cm^3, (b) 10^{-6} g/cm^3, (c) 10^{-5} g/cm^3, (d) 10^{-4} g/cm^3.



Improving Thermoelectric Properties of Gallium-Phosphide-Doped Silicon Germanium by Thermal Annealing

Space reactor thermoelectric power conversion systems use silicon-germanium (SiGe) thermoelectric cells to convert the heat supplied by a lithium-cooled fast-spectrum reactor to electric energy. The efficiency of the conversion process depends on a materials parameter *Z*, referred to as a figure of merit. Doping the SiGe with gallium phosphide (GaP) increases the figure of merit of "standard" SiGe and therefore makes the conversion process more efficient.

The Jet Propulsion Laboratory and Lewis are cooperating in an effort to maximize the figure of merit for GaP-doped SiGe by thermal annealing treatments. The GaP-doped SiGe was annealed at 1165 to 1275 °C for various times. The microstructure was examined after each annealing treatment, and the corresponding thermoelectric properties were measured.

Sample T-118, which was annealed at 1165 °C for 24 hr and then 1215 °C for 100 hr, had the highest figure of merit for any sample measured thus far—approximately 30 percent above that for the "standard" SiGe. Research is continuing to establish reproducibility and to further improve the figure of merit by varying the dopant and the dopant levels.

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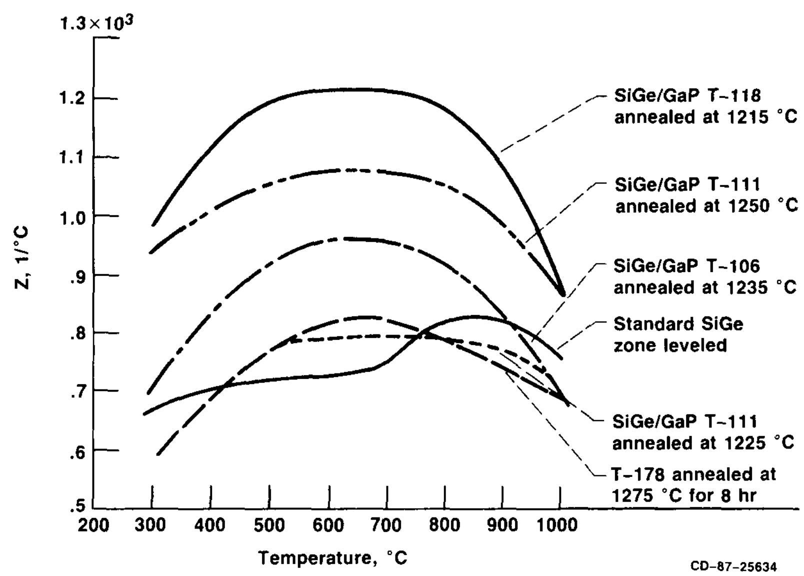

Conversion efficiency of SiGe/GaP

Stronger Intermetallics by Fiber Reinforcement

Intermetallic compounds have long been under investigation because of their inherent elevated-temperature strength and density properties resulting from their long-range ordered structures. Continuous fiber reinforcement can further enhance these properties. Lewis investigated silicon-carbide-fiber-reinforced titanium aluminide, $SiC/(Ti_3Al + Nb)$, because it has potentially better strength and stiffness and lower density than either monolithic titanium aluminide or current superalloys.

Unidirectionally reinforced $SiC/(Ti_3Al + Nb)$ composites were fabricated at Lewis by a powder cloth technique. Tensile tests were performed from room temperature to 2000 °F in the direction of the reinforcement, and the results were compared with results for monolithic $Ti_3Al + Nb$ from three published references, with similar data for a range of existing wrought superalloys, and with a single-crystal superalloy, NASAIR, to display the upper limit of superalloy capabilities at elevated temperatures. Lewis $SiC/(Ti_3Al + Nb)$ had superior tensile properties when examined on a strength/density basis.

Research is continuing to characterize the effects of fiber-matrix chemical reaction on mechanical properties, to determine long-term creep properties, and to examine transverse tensile properties over a range of temperatures. The fracture surfaces will be examined in order to better understand the nature of the fiber-matrix bond and its relation to mechanical properties.

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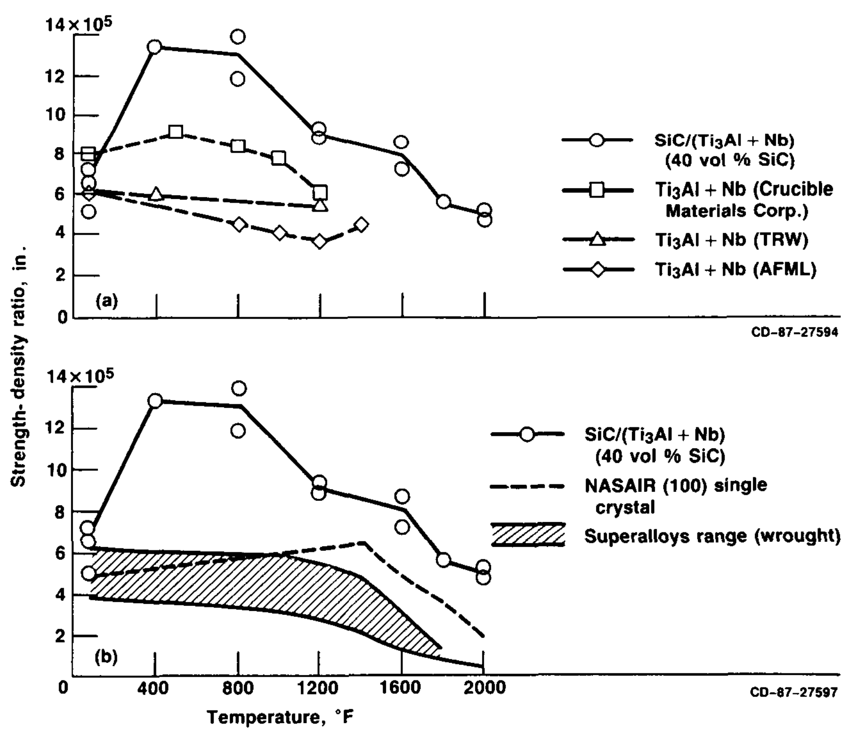
Superior tensile properties of $SiC/(Ti_3Al + Nb)$: (a) compared with unreinforced $Ti_3Al + Nb$; (b) compared with existing superalloys.



Retention of Nicalon Fiber Strength at Higher Temperatures

Many commercially available polymer-derived silicon carbide (SiC) fibers, such as Nicalon, are limited by poor thermal stability. Although these fibers offer the potential of yielding composites with high strength and toughness, they are limited to use at temperatures below 1200 °C because they lose significant tensile strength beyond this temperature. This problem also limits the fabrication temperature. In an effort to improve high-temperature fiber properties Lewis has investigated a postprocessing treatment to extend the use temperature of Nicalon fibers.

Nicalon fibers were heat treated to 2200 °C in 1360 atm of argon. The high external gas pressure inhibited the reactions that degrade Nicalon SiC fibers. High-pressure treatment delayed fiber weight loss to approximately 1600 °C and inhibited grain growth. Treatment at 1360 atm in argon delayed the onset of strength degradation by approximately 300 deg C beyond that measured for fibers treated in 1 atm of argon.

Subsequent treatments at atmospheric pressure revealed that the underlying mechanism of strength retention was the formation of a gaseous diffusion barrier that inhibits gas evolution from internal reactions and is effective only while high pressure is maintained. However, if the required composite fabrication temperature exceeds 1200 °C, high-pressure treatment extends the processing window for ceramic matrix composites.

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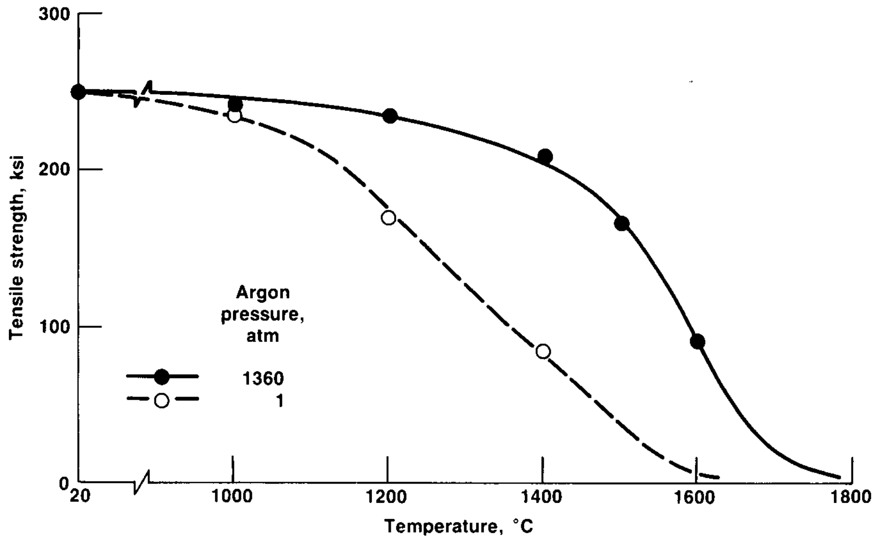

Stronger Nicalon fibers at high temperatures

Fabrication Guidelines for Silicon Nitride Matrix Composites

Reinforcing monolithic ceramics with ceramic fibers should yield materials that are stronger and more flaw tolerant than the unreinforced ceramics. However, a major technical issue in accomplishing this goal is the development of fabrication guidelines under which fibers and fiber-matrix interface properties are unaffected by the environmental and thermal conditions encountered during fabrication.

In its pursuit of structurally reliable ceramic materials Lewis has developed fabrication guidelines for strong and tough silicon nitride composites. These composites consist of high-strength, high-modulus, chemically vapor-deposited silicon carbide (SiC) fibers in a reaction-bonded silicon nitride (RBSN) matrix. A variety of fabrication conditions were used including SiC fibers with two different surface coatings and a range of nitridation temperatures and environments. Composites fabricated with SiC fibers coated with a mixture of SiC and carbon and nitrided under condition C showed higher matrix fracture strength, higher ultimate composite fracture strength, and higher strain to failure than composites fabricated with the same SiC fibers but nitrided under condition A, or composites fabricated from carbon-coated SiC fibers and nitrided under condition B. (Nitriding conditions are not given because of International Traffic in Arms Regulations (ITAR) restrictions.) The excellent strength and improved toughness of the SiC/RBSN composite fabricated under optimized conditions make it a potential material for advanced aerospace applications.

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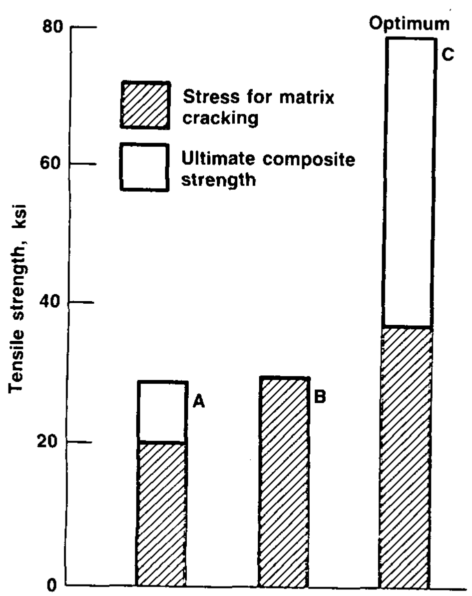

Strong and tough SiC/RBSN composites.

High-Temperature Ceramic Fibers and Composites From Silicon Polymer Precursors

Ceramics offer potential for use at high temperatures in structural applications. However, monolithic ceramics are sensitive to flaws and fail in a brittle manner. Incorporating continuous fibers into ceramic matrices can diminish the tendency toward catastrophic failure. The technology is limited at present by the availability of small-diameter ceramic fibers that retain their strength above 1200 °C and by the need for composite processing at temperatures that do not degrade the fibers.

The use of silicon-containing polymers as precursors to ceramic fibers and matrices permits low-temperature processing. By controlling molecular weight, molecular structure, and crosslinking we can tailor the rheology of the polymer for fiber or matrix formation. Complex shapes can be formed by using the technology currently available for polymer matrix and carbon/carbon composites. Finally, controlling polymer stoichiometry and molecular structure permits control of ceramic composition after pyrolysis.

Both 30- and 40-μm-diameter fibers and ceramic matrix composites have been formed at Lewis with silsesquioxane precursors. Fibers are melt spun, irradiated at 254 nm to crosslink their surfaces, then crosslinked by heating at 225 °C and pyrolyzed at 500 °C. Composites have been fabricated by filament winding and cloth layup techniques. Matrix shrinkage observed on pyrolysis suggests that these materials will be analogous to carbon/carbon composites but will have greater thermo-oxidative stability.

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ORIGINAL PAGE IS
OF POOR QUALITY

Silsequioxane-derived fibers: (a) 1400 °C argon for 30 min; (b) 1400 °C argon for 2 hr

Technique for Quantitatively Measuring Intrinsic Interfacial Strength of Brittle Films on Ductile Substrates

In all thin-film technology the adhesion between film and substrate is of crucial importance. Film adhesion is affected by extrinsic factors such as the environment, the applied stress, and the internal stress in the film and by the intrinsic bond strength between the film and the substrate. Lewis has been working to develop a quantitative technique for determining the intrinsic interfacial bond strength.

Thin films of some metals (e.g., iron, nickel, and cobalt) deposited on a polyethylene terephthalate (PET) substrate cracked in a brittle manner when the substrate was strained uniaxially. The cracked segments ultimately debonded at their edges. The length of the first and largest debonded segment was shown to be a semiquantitative measure of the shear strength of the debonding interface. The measurement was independent of the internal stress in the film, the film thickness, and the bulk mechanical properties of the substrate. It required only knowledge of the film's tensile strength.

The technique was used to show that ion bombardment of the PET substrate before nickel deposition could raise the interfacial shear strength to the level of the PET critical shear stress. The technique is being extended to other brittle films on ductile substrates such as hard protective coatings on metals.

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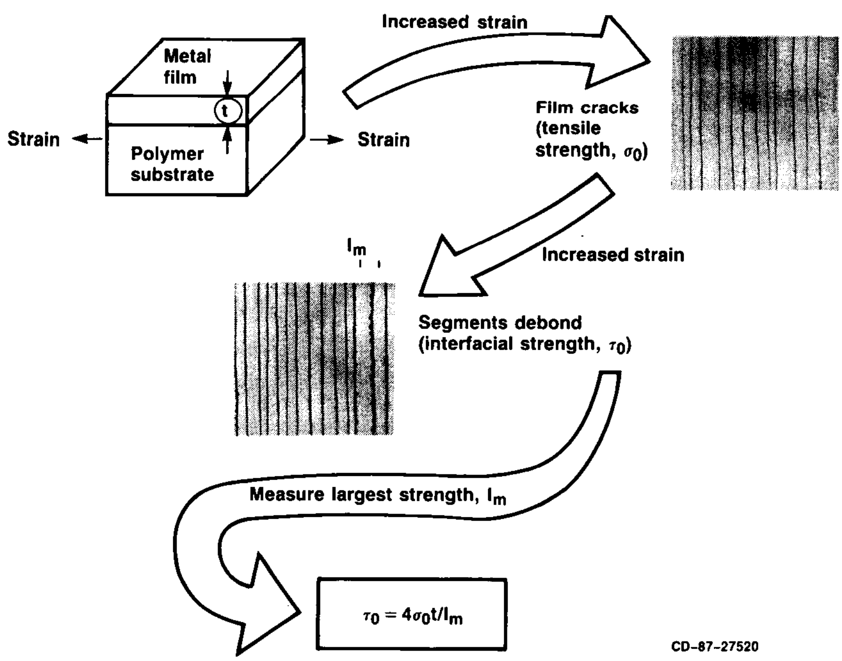

Method for determining thin fiber bond strength

Transply Crack Density Detection by Acousto-Ultrasonics

For aerospace use advanced polymer matrix composite materials must be dimensionally stable and free of cracks. Cracks degrade mechanical behavior and expose the fibers and fiber-matrix interfaces to moisture and oxygen. Graphite-polyimide composites are now replacing metals in moderately high-temperature zones (to 316 °C) in jet engines. In some applications thermal cycling introduces transply cracks into the composite structural material in significant numbers. An acousto-ultrasonics nondestructive evaluation (NDE) technique has been developed that is sensitive to the transply crack density of composite materials and can be used to monitor the propagation of such damage and thus confirm the integrity of composite structures over an expected operational lifetime. This technique is of value because it can be used to examine material damage from one surface only. Access to both sides of a structure, which is normally not easily accomplished, is not necessary. An acousto-ultrasonic apparatus was used to measure the stress wave factors of undamaged specimens and specimens with varying amounts of transply cracks. The stress wave factors decreased with increasing crack density. At high crack densities the attenuation was about the same. The acousto-ultrasonic technique holds promise as a method to assess transply crack density changes over the lifetime of composite structures.

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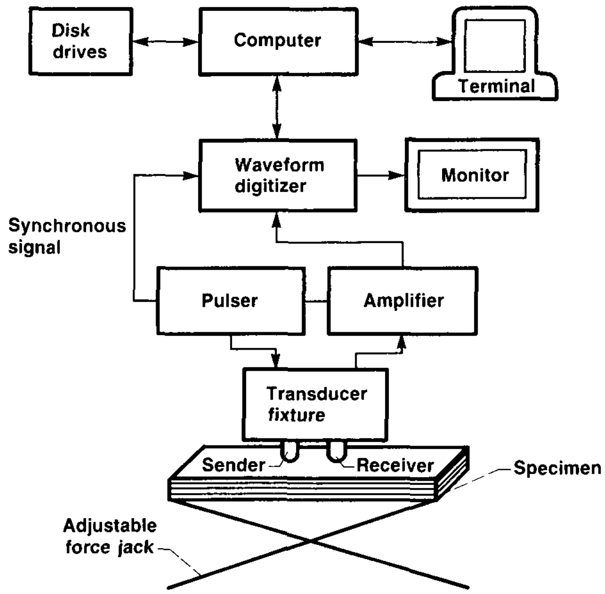

Acousto-ultrasonic apparatus and data processing system

Modeling of Chemical Vapor Deposition

Modern technology routinely uses chemical vapor deposition (CVD) to produce, coat, and infiltrate electronic, optical, and structural materials. For example, CVD coatings are used to suppress undesirable effects such as turbine blade corrosion caused by corrosive salts. Despite its wide range of applications and advances in the experimental procedures, however, understanding of the complex physico/thermochemical processes involved in CVD is rather shallow.

In an attempt to assess the significance of vapor-phase chemical kinetics in the absence of surface chemical kinetic barriers, Lewis modeled the CVD process by using two "extreme" convective-diffusion boundary layer treatments—one in which the gaseous boundary layer is taken to be in local thermochemical equilibrium (LTCE) everywhere along the diffusion path, and the other in which the gaseous boundary layer is assumed to be chemically frozen (CF). Deposition rates and condensation onset conditions (dewpoints) are predicted from these two "asymptotic" approaches for sodium sulfate (Na_2SO_4) deposition under typical atmospheric burner rig operating conditions.

The excellent agreement of the computations with experiments showed that, if LTCE is maintained at the boundaries (main stream and vapor/condensate interface), CVD rates are remarkably insensitive to vapor-phase chemical kinetics. However, the species identities, concentrations, and supersaturation levels predicted by the two theories may be substantially different, suggesting deposits with different microstructure and topography and thus different mechanical, electronic, optical, and thermal properties.

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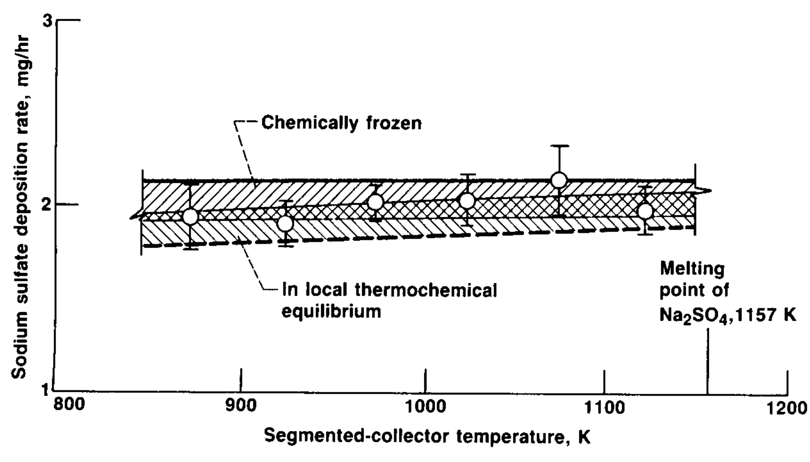

Sodium sulfate deposition rate

Fluoride Salts for Thermal Energy Storage in Advanced Solar Dynamic Space Power Systems

Solar dynamic systems operating at 1000 to 1400 K are being considered as electric power sources for future space missions. Thermal energy storage units would be required to store excess energy during the sunlit portion of each orbit and to provide energy to the power conversion system during the eclipse portion of each orbit. As a part of an in-house program on advanced solar dynamic space power systems, Lewis is investigating thermal energy storage systems based on enthalpy change associated with solid-to-liquid transformation. We are attempting to identify phase change materials with melting temperatures between 1000 and 1400 K and high latent heats of fusion per unit mass. Initial efforts have focused on inorganic fluoride salts.

Eutectic compositions and congruently melting intermediate compounds in binary and ternary fluoride salt systems have been characterized for thermal energy storage applications at 1000 to 1400 K. The melting points and eutectic compositions for many systems with published phase diagrams have been experimentally verified, and new eutectic compositions with melting points between 1000 and 1400 K have been identified. Optimum values for the melting temperatures and eutectic compositions were obtained from a coupled analysis of the thermodynamic data and the phase diagrams. Heats of fusion of several binary and ternary eutectics and congruently melting compounds were experimentally measured by differential scanning calorimetry. Several salts with high heats of fusion per unit mass (>0.7 kJ/g) have been identified for possible use as phase change materials in advanced solar dynamic space power applications. These are shown in the following table:

Composition, mol %	Melting point, K	Heat of fusion per unit mass, kJ/g
$LiF-13KF-13MgF_2$	1022	0.86
$LiF-19.5CaF_2$	1042	.82
LiF	1121	1.08
NaF	1268	.79
$NaF-60MgF_2$	1269	.71
$KF-69MgF_2$	1279	.77
$KF-50MgF_2$	1345	.71

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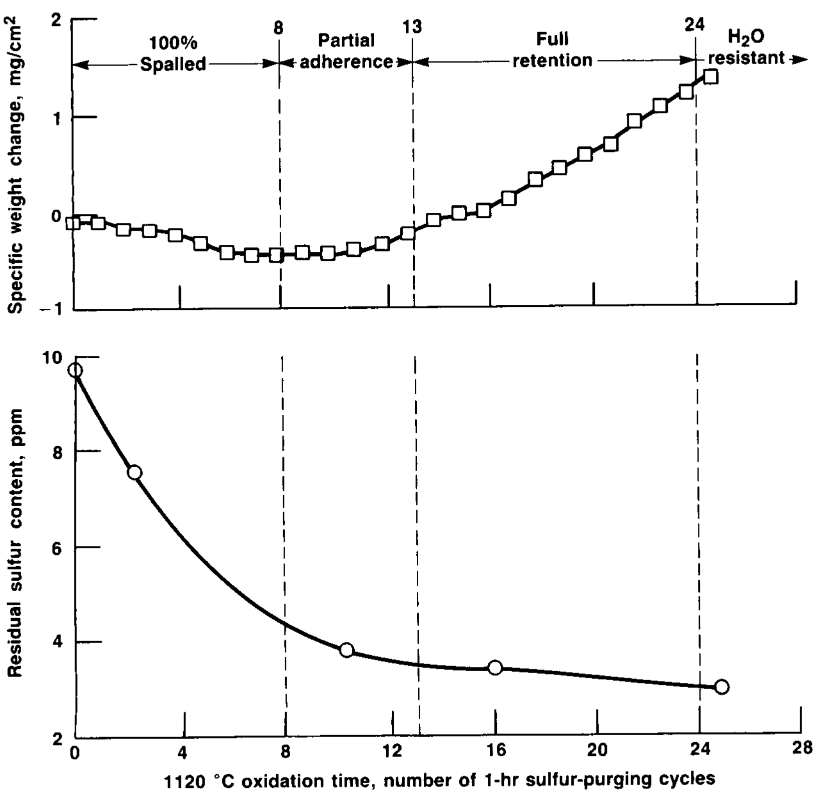
Promoting Scale Adhesion by Reducing Sulfur Impurities

It has recently been suggested that parts-per-million levels of sulfur can deleteriously affect aluminum oxide (Al_2O_3) scale adhesion on oxidation-resistant nickel-chromium-aluminum (NiCrAl) coating alloys. This hypothesis arose from hot Auger observations (1) that sulfur is a strong surface segregant even in NiCrAl alloys with extremely low sulfur contents and (2) that alloying elements which give rise to scale adhesion (yttrium, zirconium, thorium, and hafnium) also prevent sulfur segregation.

To verify the hypothesis that sulfur segregation to the oxide-metal interface destroys scale adhesion, the cyclic oxidation resistance of an Ni–15Cr–13Al alloy was examined as the sulfur content was incrementally reduced. The alloy was purged of sulfur by repeated oxidation at 1120 °C for 1 hr, and the Al_2O_3 scale was removed by polishing. Polishing also removed the highly concentrated sulfur segregation layer. Spalling (weight loss) occurred in the initial part of the experiment, as is normal for undoped NiCrAl. Full adherence and weight gains occurred after about 13 cycles. At this point the sulfur content had been reduced from 10 to 3 ppm.

Follow-on studies showed that the amount of spallation is linearly proportional to the residual sulfur content in prepurged samples and that adding 100-ppm sulfur was sufficient to destroy adherence for a zirconium-doped NiCrAl. The overall picture is consistent with the claim that sulfur interfacial segregation weakens the Al_2O_3–NiCrAl bond. These studies have substantially changed the way we look at oxide adherence mechanisms for high-temperature alloys.



Adherent Al_2O_3 scale produced on NiCrAl by removing sulfur

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Structures

Effect of Design Variables, Temperature Gradients, and Speed on Rotating Disk Life and Reliability

Lewis has devised a generalized methodology for predicting the fatigue life and reliability of a rotating disk. The method incorporates the computed life, at a given probability of survival, of elemental stressed volumes within the disk body to arrive at total disk life and reliability. The effects on disk life of speed and such design variables as disk diameter and thickness and the size, number, and location of bolt holes were determined. The effect of a radial temperature gradient as well as the accompanying induced thermal stress on the relative life of the disk were also investigated. In addition, material characteristics such as Weibull modulus and fatigue limit were incorporated into the methodology.

From the analysis the concept of a dynamic speed capacity N_0 is introduced. This is defined as the speed that would produce a theoretical life of 1 million stress cycles at a 90-percent probability of survival. For any speed N the life L for a given disk geometry at a 90-percent probability of survival is $L = (N_0/N)^{14.3} \times 10^6$. This method can be practically applied in analyzing, designing, and developing aircraft engine turbine and compressor disks as well as flywheels for industrial and automotive applications.

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Design of Fiber Composites for Structural Durability

A computational methodology has been developed and is available at Lewis to design and analyze fiber composite structures subjected to complex hygrothermomechanical environments. This methodology includes composite mechanics and advanced structural analysis methods (finite element). To illustrate the application of the available methodology, various composite design applications can be addressed such as composite progressive fracture, composite design for cyclic fatigue combined with hot-wet conditions, and general composite laminate configurations.

A major concern in the fiber composite community has been the prediction, or even a reasonable approximation, of the structural durability of fiber composite structures in service environments. Fiber composite structures need to be designed to resist such service environments as mechanical load (static, cyclic, and impact), heat, moisture, and combinations of these conditions called hygrothermomechanical (HTM) environments. The general procedure for designing fiber composites for HTM environments is to use empirical data to select laminate configurations for the component, to validate them through the preliminary design phase, and then to conduct a variety of tests in the specified HTM environments. The results for these tests are used to reconfigure the laminates to meet the design requirements in these environments.

This procedure, although successful, is costly and time consuming and has to be repeated for each new design. It can be largely circumvented by a methodology for predicting the structural durability and therefore the service life of fiber composites in HTM environments. The computational methodology developed accurately predicts the HTM effects on fiber composite stiffness and strength and thereby can be used to design fiber composite structural components for structural durability. This computational methodology has evolved over the past 7 years. It began with the development of an integrated theory for predicting hygrothermal effects on fiber composites and has culminated in three major computer programs: CODSTRAN (Composite Durability Structural Analysis), INHYD (Intraply Hybrid-Composite Design), and ICAN (Integrated Composite Analyzer). These programs collectively provide analyses required to design for structural durability in HTM service environments.

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Cowl Lip Leading-Edge Concepts for NASP

A critical problem area in developing an aeropropulsion system for a hypersonic flight vehicle is the high heat flux associated with such phenomena as high-dynamic-pressure compression surfaces, shock–boundary layer interactions, and high-enthalpy combustion chamber processes. In the leading-edge region, not only must the maximum heating rates be tolerated, but distortions to the flowfield caused by excessive blunting and thermal warping of the compression surface must be held to a minimum if high inlet performance is to be achieved. Moreover, slender, relatively sharp shapes are customary, and therefore little heat is conducted away from the hottest regions. In addition, the flat, relatively large-surface-area panels in the combustion zone are also subject to high heat flux and must be actively cooled to maintain structural integrity. Lewis has formed a cowl lip technology (COLT) team to assess and evaluate the thermal and structural technology issues associated with the propulsion system inlet region of the proposed National Aerospace Plane (NASP).

A hydrogen-oxygen rocket engine has been modified to use the exhaust stream as a source of high enthalpy and high heat flux. This engine will be used to evaluate various actively cooled simulated cowl lip segments and flat structural segments. The facility can provide heat flux levels from about 200 to 10,000 Btu/sec ft^2. Reynolds number similarity can be matched throughout this range such that even though Mach number is not simulated a priori, the heat transfer phenomenon is representative of flight Mach numbers of 5 to 7. The maximum heat flux is comparable to that obtained at flight Mach numbers to 24.

The facility capabilities have been calibrated during the past year. Both crossflow and regenerative models have been tested with a generic cooling configuration and water and gaseous hydrogen as the coolants. In addition, various types of materials have been compared, ranging from high-conductivity copper to typical superalloys to metal-matrix composites. Three-dimensional finite-element models of crossflow and regenerative cowl lip concepts were developed on the software package PATRAN-G for analysis in NASTRAN. Steady-state heat transfer analysis was performed by assigning ambient gas temperatures and conductive film coefficients, determined by STAN5, to the model. The resulting nodal temperatures were then used as input to a thermal stress analysis of the same model. These analyses were performed for copper, nickel, and metal-matrix composite material properties.

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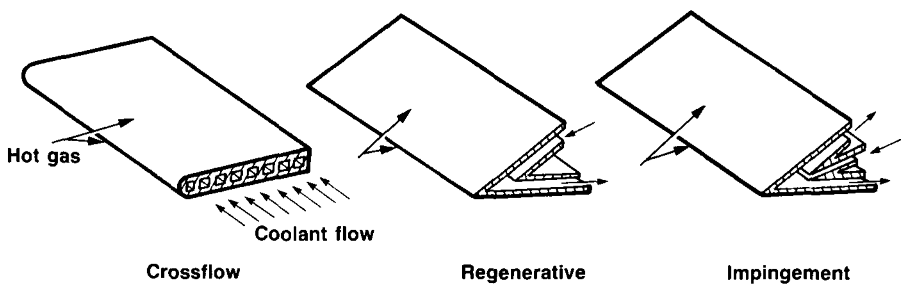

Cowl lip cooling concepts

3D TRANCITS—A Computer Analysis Program for Interfacing Thermal and Structural Codes

Considerable effort in the past 20 years has been devoted to the development of heat transfer computer codes for predicting steady-state and transient temperatures, as well as to non-linear finite-element codes for predicting cyclic stresses and strains. In applying these sophisticated analytical methods to complex three-dimensional engine components, a serious problem has developed in interfacing output temperatures and temperature gradients from the heat transfer analysis codes with the structural analysis codes. This problem has been further exacerbated by the growth in computer capacity and speed and the development of input preprocessors and output postprocessors. With these advances the analysis of components using hundreds and even thousands of nodes in the heat transfer and structural models has become economical and routine. Doing the interfacing manually or with simple coupling codes for complex models is out of the question.

A software package has thus been developed to transfer three-dimensional transient thermal information accurately, efficiently, and automatically from a heat transfer analysis code to a structural analysis code. The code is called the Three-Dimensional Transfer Analysis Code to Interface Thermal and Structural Codes, or 3D TRANCITS. 3D TRANCITS can couple finite-difference and finite-element heat transfer analysis codes to linear and nonlinear finite-element structural analysis codes. It currently supports the output of the SINDA and MARC heat transfer codes directly. It will also format the thermal data output directly so that it is compatible with the input requirements of the NASTRAN and MARC structural analysis codes.

Other thermal and structural codes can be interfaced by using the transfer module with the neutral heat transfer input file and the neutral temperature output file. The transfer module can handle different elemental mesh densities for the heat transfer and structural analyses. The architecture of the code is such that 3D TRANCITS is both user friendly and easily modifiable. The code is constructed in modular form so that future modifications or even different applications (pressure or boundary condition transfer, for instance) can be accomplished without a full rewrite.

3D TRANCITS is written in Fortran IV. It has been run on Honeywell, IBM Cray, and VAX computer systems.

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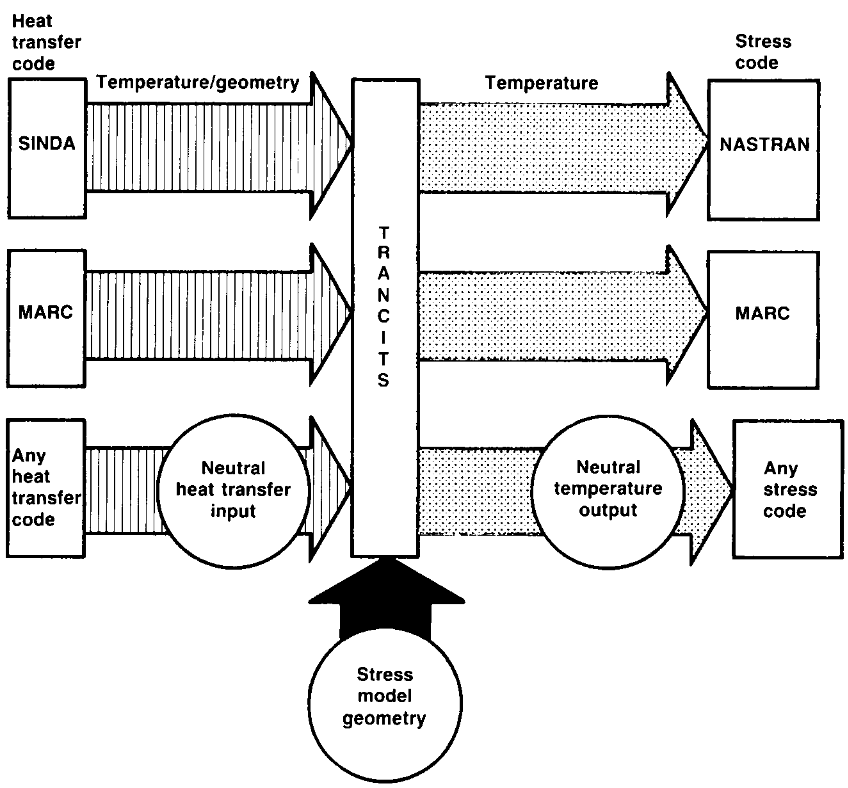

Program schematic for 3D TRANCITS

Micromechanics Equations for High-Temperature Metal-Matrix Composites

The mechanical performance and structural integrity of fiber-reinforced metal-matrix composites are generally functions of the behavior of the constituent materials at the micromechanics level. It is not uncommon for all the individual constituent materials to exhibit significantly different behaviors. Moreover, constituent behavior is dynamic, particularly in high-temperature applications, where the materials are continuously changing character because of the nonlinearities associated with large local stress excursions, temperature-dependent material properties, time-dependent effects, and constituent chemical reactions.

In the structural analysis of a metal-matrix composite it then becomes highly desirable to describe and track this dynamic constituent behavior at the micromechanics level. Available methods for doing this are limited. Techniques such as three-dimensional finite-element analysis could in principle be applied directly, with the constituents modeled individually through the discretization. However, for complex structures the resources (human and computer) required to define, conduct, and interpret such an analysis become prohibitive. Another approach is to employ composite micromechanics theory to derive simplified expressions relating the anisotropic behavior of the basic composite unit (e.g., a unidirectional ply) to the behavior of the individual constituents. Lewis has taken this approach as part of a comprehensive program to develop novel computational mechanics methodologies for advanced composite propulsion structures.

As an essential part of this program a unique set of micromechanics equations has been derived for high-temperature metal-matrix composites. This set comprises closed-form expressions to predict equivalent "pseudohomogeneous" properties for the unidirectional fiber-reinforced ply, including mechanical properties (moduli and Poisson's ratios); thermal properties (conductivities, expansion coefficients, and heat capacity); in-plane uniaxial strengths; and constituent microstresses.

The equations were derived by using a mechanics-of-materials formulation assuming a square-array unit cell model with a single fiber, a matrix material, and an interphase. Concurrent with the derivation, a preliminary validation study was performed by using three-dimensional finite-element analysis to assess the general applicability of the formulation and to evaluate the accuracy of the equations for a specific composite system. The study demonstrated excellent agreement between micromechanics-predicted equivalent properties and those simulated in the finite-element analyses.

The equations were implemented as part of an integrated computational capability for the nonlinear analysis of high-temperature, multilayered fiber composite blade structures. Their utility in this particular implementation is demonstrated with a few typical examples taken from an analysis of a tungsten-fiber-reinforced superalloy turbine airfoil.

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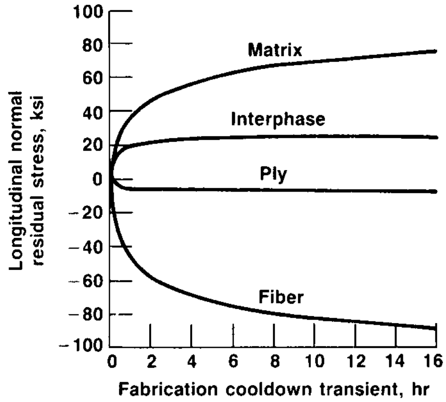

Analysis of fabrication-induced stresses on turbine airfoil

Theory of Viscoplasticity Based on Dislocation Climb

A general theory of viscoplasticity has been derived from a potential function in accordance with thermodynamics and the physical constraint of material stability. Two internal state variables were considered: one to account for isotropic effects; the other to account for kinematic effects (flow-induced anisotropy). The internal variables evolved with the competing mechanisms of work (or strain) hardening and thermal recovery (or annealing).

Specific structure was given to the functional forms of the general theory by comparing it with a micromechanical theory for steady-state creep through dislocation climb. The theory incorporates a smooth transition from a power-law response to an exponential response. The material response is less rate sensitive in the exponential region than it is in the power-law region.

The resulting continuum theory of viscoplasticity has been used to model the response of nickel under a variety of loading conditions. It predicts reasonable material responses very well.

Experiments are now being planned to determine how accurate the theory is under nonisothermal conditions. It is expected to do well under these conditions as long as the dominant deformation mechanism does not change.

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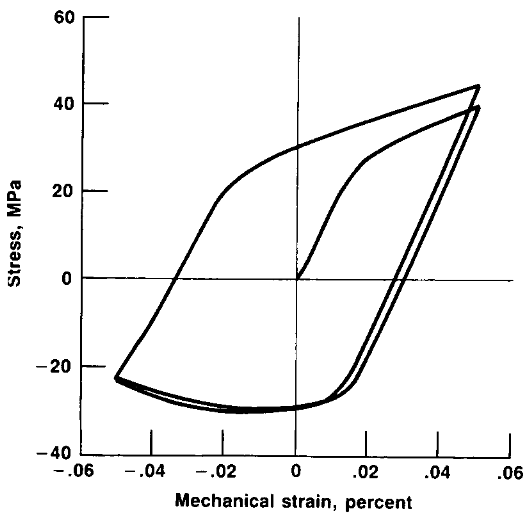

Predicted, out-of phase thermomechanical hysteresis loop for nickel at 500 to 1000 °C

Discrete Bearing/ Roller-Drive Rotary Joint for Space Station

Solar power conversion units for the space station must be able to track the Sun at an approximate orbital rate of one revolution every 94 min. The most critical mechanism aboard the station will be the rotary joint that performs this tracking function. It must position the solar receivers to within about 1° normal to the Sun for a photovoltaic receiver and to about 0.1° for a solar dynamic collector. Because of the large inertia of the solar receivers and the length of the transfer booms, structural stiffness across this rotary joint must be maximized to reduce deflection and acceleration as well as to maximize actuator response rate. The joint also must contain a means to transfer electric power and data signals across the rotary interface. Furthermore the rotary drive mechanism must provide smooth motion, possess long life in a space environment, and have intrinsically fail-safe characteristics. Lewis conducted a study to determine the optimum mechanism for the rotary joint. The results indicated that the best mechanism would be a continuously rotating joint that was based on the concept of a multiple, discrete-bearing-supported joint driven by a self-loading, "pinch" roller-drive actuator. This mechanism would provide greater protection against catastrophic jamming, less sensitivity to adverse thermal gradients, greater accessibility for maintenance or replacement, and greater adaptability to large truss members than more conventional continuous-support bearing/gear joints. Furthermore wear life estimates show a continuous service life more than two orders of magnitude greater than required for this application.

This rotating joint mechanism would be applicable not only to solar power conversion units, but also to Earthbound solar power farms and other related power generation systems.

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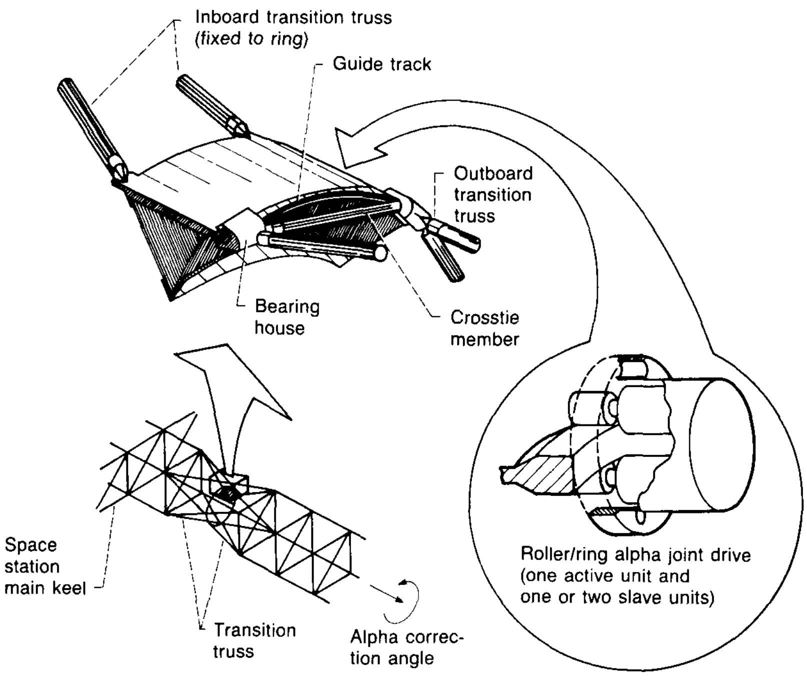

Rotary joint concept

Constitutive Law for Finite-Element Contact Problems With Unclassical Friction

Designers of advanced turbine engines are investigating making turbine blades of high-temperature (2500 °F) lightweight ceramics to improve engine efficiency and thrust-to-weight ratio. Preliminary tests with ceramic turbine blades, however, have uncovered problems in attaching the stiff ceramic blades to the metal turbine disks.

Lewis is developing a computational procedure for determining detailed stress and displacement information at the critical blade-root/disk interface to help designers optimize geometry for minimal frictional contact stresses. The displacement-based finite-element method uses constitutive modeling concepts to relate increments of contact surface stress to contact surface deformation. Resultant normal and tangential stresses are determined from deformations (decomposed into elastic and plastic components) through a general elastoplastic material matrix that accounts for the surface roughness, the relative mating of the contact surfaces, and a appropriate surface friction law.

For the unlubricated two-body contact problem considered, a three-term general friction law was formulated that accounts for plasticity of the contact surface film layer, adhesion due to molecular attraction, and plowing due to penetration of contacting surface asperities. The value of each of these frictional components can be tailored to the specific problem. Furthermore the incremental form of the constitutive relation allows modeling of complex load deformation histories, typical of the blade-root/disk problem, that can account for reversals of sliding direction at any time.

A computer program employing this modeling concept is being developed. Information generated from this program will be used in the design and development of advanced turbines.

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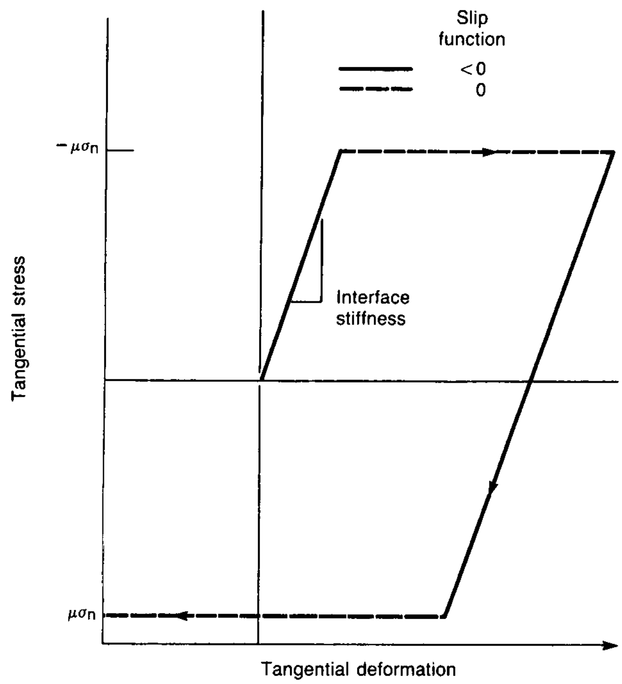

Possible two-body stress-deformation response (constant normal load, σ_n; friction coefficient, μ)

Stiffness and Damping of Tapered-Bore Seals

It is well known that annular seals (ring seals) can generate significant lateral forces and that these forces can strongly influence the dynamics of shaft systems. Analyses have predicted that tapered-bore seals (with the clearance diminishing in the flow direction) will have a higher stiffness than straight-bore seals for both incompressible and compressible fluids. Moreover, for compressible fluids straight-bore seals can sometimes have a negative stiffness, which is nearly always undesirable.

Tests were conducted at Lewis on a vertical shaft supported radially by two pairs of tapered-bore seals. A dynamic load was produced by unbalancing the shaft a known amount. Dynamic motions were measured with capacitance distance probes and a digital vector filter. These motions were input to the shaft equations of motion, which were then solved for stiffness and damping coefficients. Typically there was little change in stiffness with pressure ratio. The small variance is also predicted by analysis. Measured stiffness was somewhat higher than predicted, but within 30 percent. Measured damping coefficients were much lower than predicted probably because the one-dimensional analysis used assumed flow in only the axial direction.

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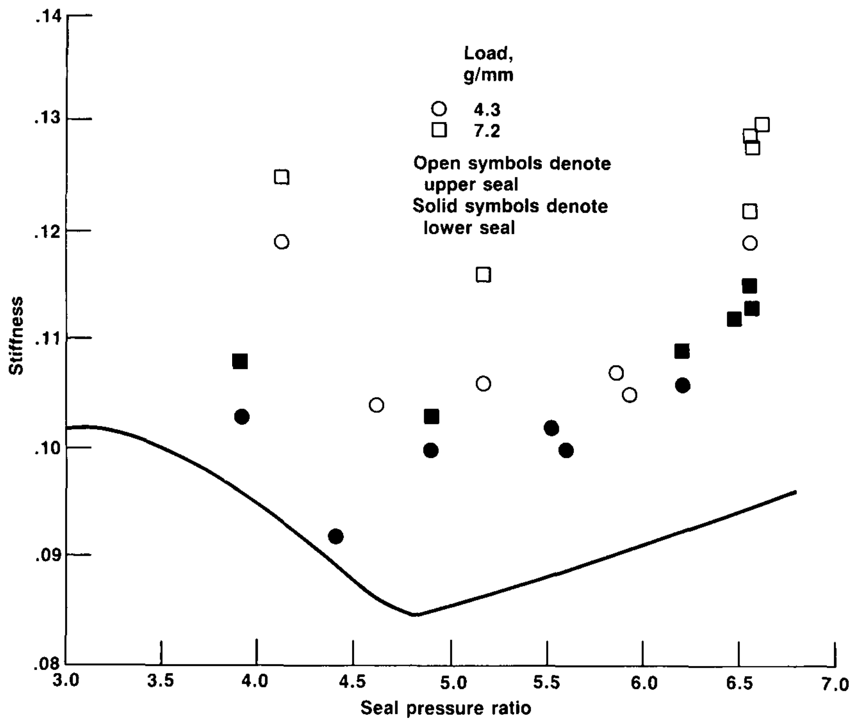

Stiffness of tapered-bore seals

Low-Cost Optical Data Acquisition System for Vibration Measurement

An optical data acquisition system can simultaneously measure the vibration deflections of all the blades on a spinning rotor and can provide a complete vibration record for each rotor blade. Unlike a strain gage measurement system with its slipring capacity limitations, the optical system can measure the response at several positions of every blade on a multiblade rotor. The optical system measures vibration directly, without the calibration problems inherent to a strain gage measurement system. Signal processing and analysis are facilitated in the optical system because data are taken in digital form.

A major disadvantage of the existing optical system in the Lewis spin rig is that its relative complexity makes it costly and difficult to maintain or repair. Efforts to simplify the system and produce a low-cost version were prompted by the need for additional optical data acquisition capability to cover independent operation of another spin rig and an advanced version of a rotating system dynamics rig.

The basic principle of the new design is to record raw data (a set of blade arrival times) in memory and to perform all processing by software after a run. This approach yields a simple and inexpensive system with the least possible hardware. Blade arrival times are measured from the start of a run rather than from the start of each rotor revolution. This eliminates the need for costly frequency synthesizers in the new system. The data acquisition boards are configured to accept inputs from as many as four optical probes. This reduces the number of data acquisition boards required to monitor a common blade tip region from 32 to 8. The total number of integrated circuits required in the new system is reduced from 2317 to 283. Though the hardware was significantly reduced, basic performance characteristics such as maximum allowable deflection, deflection resolution, maximum (unaliased) frequency, and frequency resolution were not compromised. Performance was improved for most operating conditions.

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Flutter Investigation of Composite Propfan Model

A theoretical model and computer program called ASTROP has been developed for predicting subsonic bending and torsion flutter in propfans. One version of the code, ASTROP2, uses two-dimensional subsonic unsteady (cascade) aerodynamics; another version, ASTROP3, uses three-dimensional subsonic steady and unsteady (cascade) aerodynamics. In both versions a finite-element model, currently NASTRAN, represents the blade structure.

Theoretical results have been correlated with flutter data taken on a wind tunnel propfan model with four and eight composite blades at a blade pitch angle of 61.6°. The calculations were from ASTROP3 and included the effects of centrifugal loads and steady-state air loads. The theory predicted the flutter speeds and the slopes of the boundaries reasonably well. However, the difference between the calculated and measured flutter Mach numbers was greater for the four-blade case than for the eight-blade case. Thus the theory may be overcorrecting for aerodynamic cascade effects for four blades. Similar comparisons made at blade angles of 56.6° and 68.4° showed approximately the same agreement. Calculated interblade phase angles at flutter also compared well with measured values. However, calculated flutter frequencies were about 8 percent higher than measured. Both theory and experiment showed that increasing the number of blades on the rotor and increasing the blade pitch angle are destabilizing.

Analysis showed that flutter speed predicted by two-dimensional aerodynamic theory is less accurate than that predicted by three-dimensional theory. Hence final design calculations should be done with three-dimensional analysis. The influence of steady-state aerodynamics on blade-deflected steady-state geometry, blade mode shapes, and flutter speed can be significant and thus should be included in final design calculations.

The effects of mistuning on propfan subsonic flutter have been analytically and experimentally investigated. A mistuned wind tunnel model was constructed by alternately mounting two sets (SR3C-X2 and SR3C-X3) of composite blades. These blades were molded from graphite ply/epoxy matrix laminates with different ply directions. The analytical model was validated for selected cases by comparing predicted and measured flutter characteristics of the (mistuned) wind tunnel rotor (SR3C-X2/SR3C-X3).

Additional parametric studies showed that combined mode shape, frequency, and aerodynamic mistuning can either beneficially or adversely affect blade damping, depending on the Mach number range. Alternate-frequency mistuning did not have enough potential to be used as a passive flutter control in propfans similar to the one tested in the present investigation. Theoretical and experimental results show that a laminated composite propfan blade can be tailored to optimize its flutter speed by properly selecting the ply angles.

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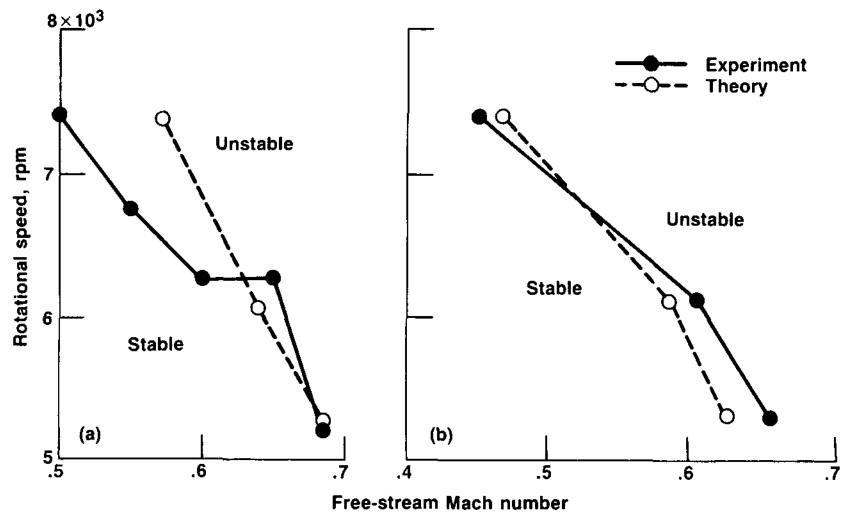

Measured and calculated flutter boundaries for SR3C-X2 propfan model (blade angle (0.75R), 61.6°): (a) four blades; (b) eight blades

Parallel Eigenanalysis of Finite-Element Models Using Multifrontal Method

A finite-element model can be divided into a series of pieces or domains where each domain contains a subset of the finite elements. If each domain is treated separately, the mathematical degrees of freedom of the finite-element model can be divided into two sets: those degrees of freedom within each domain, and those along the boundaries. Each domain may be independently assigned to separate parallel processors for the solution of internal degrees of freedom. Compatibility between domain boundaries can be achieved with a global processor. With this approach a finite-element model is divided into n domains and assigned to n domain processors. An $(n + 1)^{th}$ processor performs global operations.

The multifrontal method offers a new parallel algorithm for the solution of the generalized linear eigenproblem, which is typically encountered in finite-element modeling of linear systems. The algorithm is based on the classical frontal method for solving linear simultaneous equations and on the modified subspace method for solving the eigenproblem. Each domain processor is assigned to solve for the degrees of freedom within each domain exclusive of those degrees of freedom located along the boundary. Concurrently each processor creates the stiffness and mass matrices of its elements by performing simultaneous assembly, forward elimination, and backsubstitution. The modified subspace eigenanalysis method also exploits parallelism by projecting the stiffness and mass matrices through each domain.

The global processor is assigned the task of solving the global front, which comprises the boundaries of all domains. It is also given the task of summing the contribution of the domains to the current subspace eigenvalue iteration. The multifront can be visualized as sweeping all domains concurrently in forward and then backward directions. This process can be repeated until each domain converges.

Communication between processors is machine dependent. This dependence is being studied on a variety of machines. Future work will investigate the effect of dividing the domains into subdomains so that the domain processor functions as the global processor to the associated subdomains. In this fashion a finite-element analysis can be placed within a tree-like array of parallel processors.

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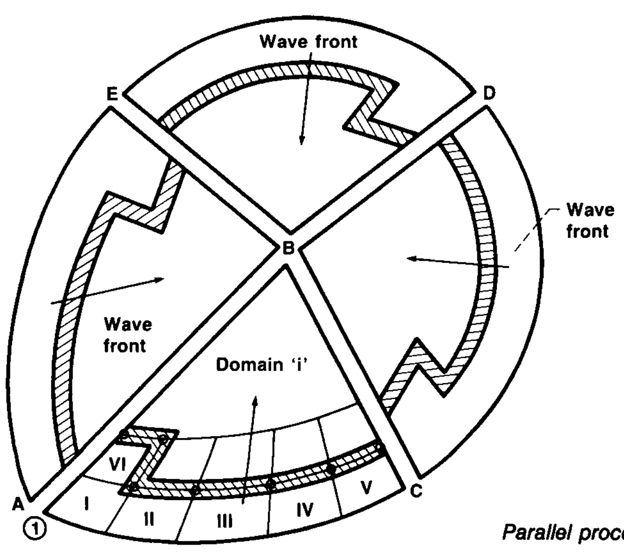

Parallel processing within domains

Characterization of Structural Connections

Lewis has carried out an analytical and experimental program to develop improved methods for characterizing connections between structural components. Of particular interest was identifying stiffness properties. The procedures developed in this program were evaluated with experimental vibration data obtained from the rotating system dynamics rig.

Deficiencies in existing modeling techniques limit the analyst's ability to adequately model the connections between components. Connections between structural components are often mechanically complex and can profoundly influence overall system behavior. Thus, to refine the prediction of overall system behavior, improved analytical models for connections are needed.

Modeling accuracy is improved by using optimization methods to reduce discrepancies between the measured characteristics of an actual structural system and those predicted by an analytical model of the system. The approach used in this work involves modeling the system components with either finite elements or experimental data and then connecting the components at their interface points. Experimentally measured response data for the overall system are then used in conjunction with optimization methods to improve the connections between components. The improvements in connections are computed in terms of physical stiffness parameters so that the physical characteristics of the connections can be better understood.

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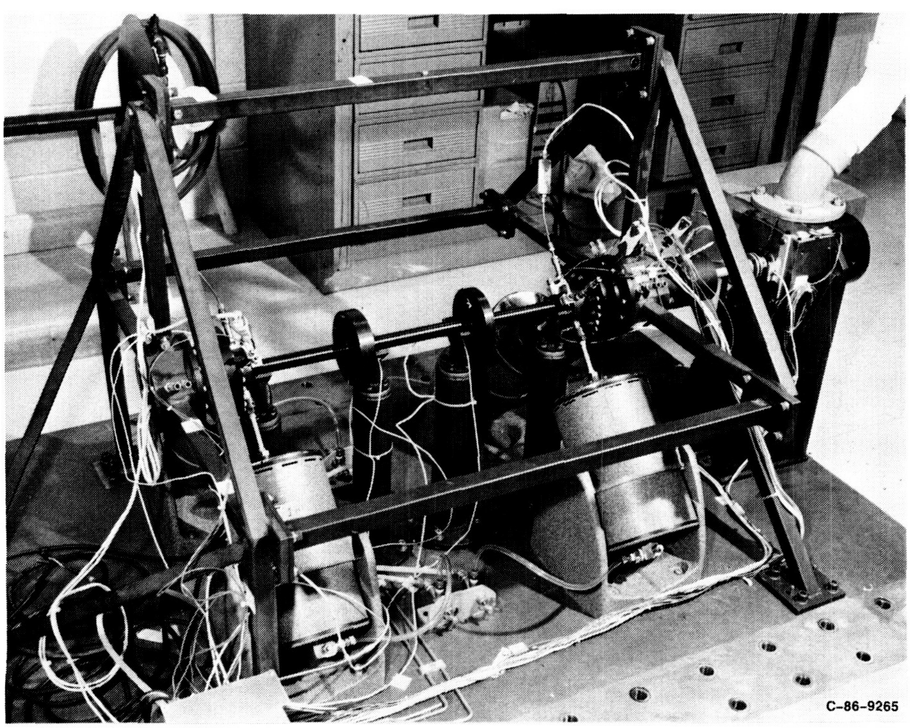

Rotating system dynamics rig

Completion of Third-Generation Wind Turbine

The Mod–5B wind turbine, the final step in the Federal Government's current program to develop megawatt-scale, horizontal-axis wind turbines, is about to go online as a nonpolluting powerplant on the Hawaiian Electric Industries Company grid at the northern tip of the Island of Oahu. This wind turbine, the world's largest of its type, brings together all of the lessons learned during the past 15 years of intensive wind energy technology development at Lewis. The specific objective of the project was to demonstrate reliable, cost-effective operation of a large wind turbine generator in a utility environment.

The machine's rated power is 3.2 MW. The rotor, which spans 320 ft tip to tip and weighs 320,000 lb, drives a power train inside a closed nacelle atop a 200-ft tower. All major structural assemblies are medium-grade welded steel. The total weight bearing on the foundation is 939,000 lb. During utility operation the Mod–5B is expected to generate more than 15 million kW-hr of electric energy annually throughout its 30-year design life.

Overall direction and funding was provided by the U.S. Department of Energy, with design and construction by the Boeing Aerospace Company, as the prime contractor, under Lewis management. After 6 months of extensive testing by NASA, the machine will be sold to the Hawaiian Electric Industries Company.

The significance of the Mod–5B lies mainly in its advanced technology. In addition to innovations pioneered on its immediate predecessor, the Mod–2 wind turbine—such as an upwind teetered rotor, a compact planetary gearbox, and pitchable tip control—the Mod–5B employs a variable-speed electrical induction generator and control system. This system permits the rotor to turn at various speeds over a limited range in order to better match the varying winds and produce more energy through greater efficiency. Previous large wind turbines were restricted to operation at a fixed rotor speed because of the requirements of their constant-frequency, synchronous generators. In addition to increased efficiency, variable-speed operation smooths out drive train and rotor tip vibrations and reduces fatigue loading because the rotor tips do not have to constantly cycle in gusting winds.

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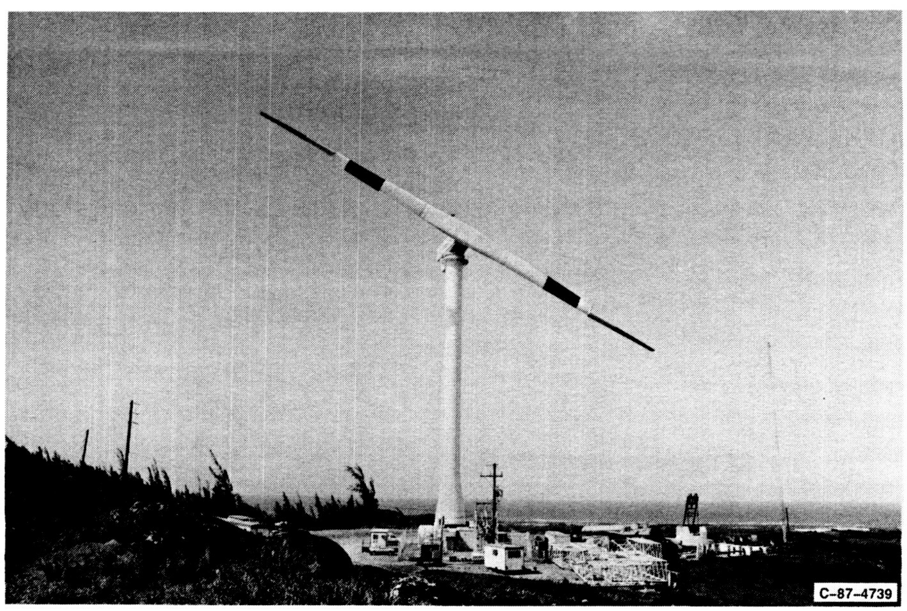

Mod–5B wind turbine in Hawaii

Determining Directions of Ultrasound in Solids

Ceramics, being investigated as replacements for metal components in engines, exhibit both low toughness and wide variability in strength. This is generally attributed to impurities, voids, or microcracks introduced during processing. Locating such flaws is important in determining whether a manufactured component is fit for service.

Scanning laser acoustic microscopy (SLAM) uses high-frequency ultrasound in conjunction with a laser to produce acoustic images of specimens on a video monitor. These acoustic images are analogous to optical images. Depths of flaws within opaque specimens can be predicted by using a stereoscopic method with SLAM. Determining flaw depth accurately requires precise knowledge of the direction in which ultrasound travels within a specimen. This direction can be calculated from Snell's relation if the velocity of ultrasound in the material is known and if the specimen surface is acoustically flat and smooth.

Lewis has developed an improved method for determining the direction of ultrasound in materials by using SLAM. This innovation, called the shadow method, is applicable to a wide range of surface roughnesses. In this method a rectangular groove cut into the surface of a specimen blocks the ultrasound signal from reaching a limited area of the surface. On the video screen this area shows up as an extremely dark (low sound intensity) region in contrast to adjacent areas in the acoustic image and is defined as the shadow region.

The direction of ultrasound, as denoted by the angle B, is determined by the simple trigonometric relationship $B = \tan^{-1}(L/H)$. The shadow method has been used to precisely determine the directions of ultrasound in ceramic, glass, and plastic specimens with surface finishes ranging from highly polished to as fired. From these directions the stereoscopic method has been used to predict the depths of flaws in these specimens quite accurately. This method may have a variety of applications in nontraditional quality-control applications.

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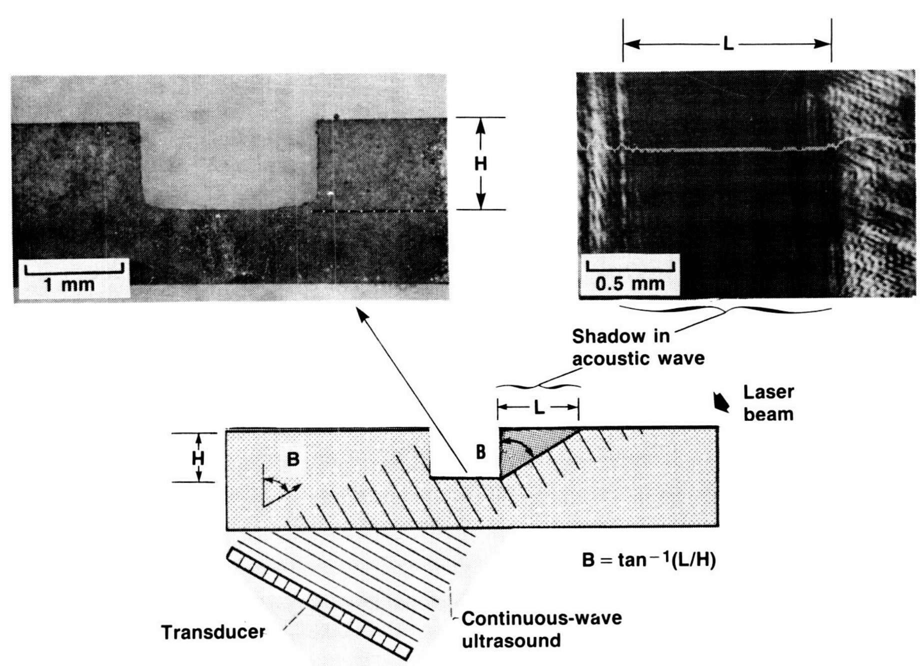

Shadow method for determining directions of ultrasound in solids

Statistical Reliability Test of Nondestructive Evaluation Techniques

Lewis has developed a statistical test for characterizing the flaw-detecting capabilities of sophisticated nondestructive evaluation (NDE) techniques. This test has been used to determine the reliability of several state-of-the-art NDE techniques for detecting failure-causing flaws in advanced ceramic materials being considered for use in automobiles, airplanes, and space vehicles. Reliability is difficult to assess since the results are influenced by many variables, including the flaw shape and orientation, the surface texture and microstructure of the material, and the day-to-day variability of the performance of the equipment and the operator.

In the statistical test specially prepared specimens (of a specific material) containing artificially seeded and controlled flaws are examined by NDE. Data are gathered on the number and size of flaws detected or not detected. The data are analyzed with a detailed computer program involving binomial-distribution statistics, and the reliability is displayed graphically in terms of the probability of flaw detection as a function of the flaw type and size. Lewis used this method to determine the reliability of two sophisticated NDE techniques (scanning laser acoustic microscopy and microfocus x-radiography) for detecting different flaw types in structural ceramic material.

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Estimating Crack-Extension-Resistance Curve

A new analytical method enhances the capability to determine the crack-extension-resistance curve, or *R*-curve, of a sample. The *R*-curve, one of the most powerful techniques available to an analyst of material fractures, can be used to predict failure loads for any initial crack size in any specimen or structure for which a stress-intensity analysis is available. To determine the *R*-curve, precracked specimens are tested with special displacements measured continually to failure. In the past, however, often the only data taken and reported were the initial crack length and the maximum load. In the new analytical method the *R*-curve can be estimated from residual-strength data alone, provided that the quantity and quality of data are adequate to permit numerical differentiation with confidence. For some applications an estimate may suffice. For others the estimate will help set up an efficient *R*-curve test plane. The method has been verified against data from the literature and in a predictive blind round-robin program.

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Acousto-ultrasonic Measurements of Composite Interlaminar Shear Strength

Lewis has developed an acousto-ultrasonic technique that uses a computer and a waveform digitizer to nondestructively evaluate composite materials. The technique was developed to verify the integrity of large composite structures and to ensure damage detection and reusability. It has been employed on filament-wound composite specimens cut from sample segments of graphite epoxy cylinders. Similar applications of the technique are anticipated for a variety of composite structures such as pipelines and storage tanks.

In the acousto-ultrasonics technique the specimen is first measured nondestructively. The output pulse is then digitized and processed in a computer to generate the stress-wave factor. Next data from bend tests are used to calculate interlaminar shear strength. Frequency spectra of the digitized acousto-ultrasonic output signals are obtained by employing a fast Fourier transform algorithm. And the stress wave factor is then calculated for a variety of filter ranges.

The reliability of the stress wave factor as a predictor for interlaminar shear strength in filament-wound composites was tested by performing a regression analysis of the stress wave factor data with the bend test data. The major portion of the spectrum was insensitive to interlaminar shear strength.

Work is in progress to more clearly define the influence of frequency filtering on the value of the stress wave factor as a predictor for mechanical properties in filament-wound composite materials and structures.

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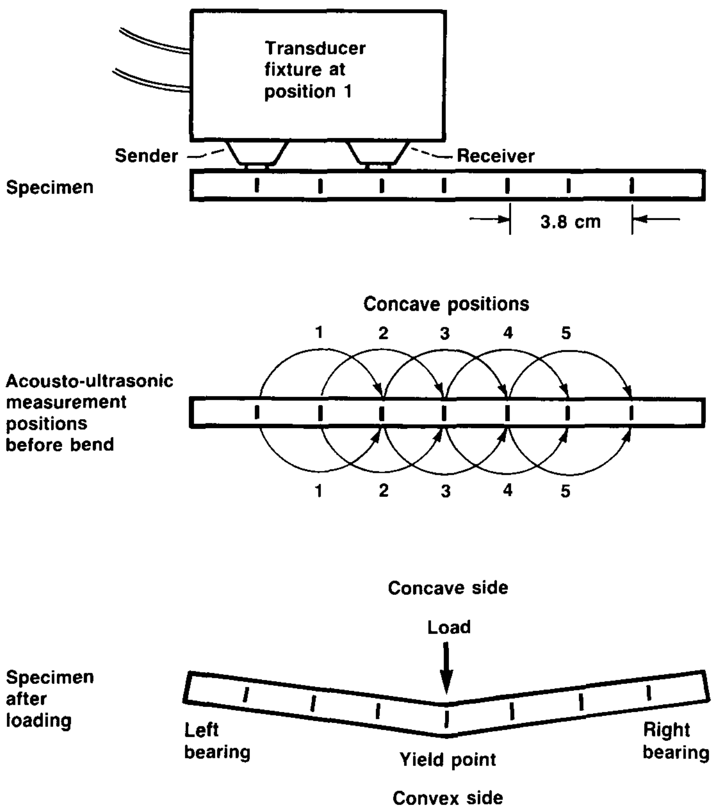

Relative orientation of acousto-ultrasonic measurements and bend test support points

SCARE—A Code For Reliability Analysis of Ceramic Structural Components

The potential use of structural ceramics for high-temperature applications depends on the reliability of these materials. A code called SCARE (Structural Ceramic Analysis and Reliability Evaluation), developed at Lewis, is used for computing the statistical fast-fracture reliability of structural ceramic components. The program contains the two-parameter model of the Weibull material (fracture strength) probability-of-failure distribution. For polyaxial stress states the principle of independent action or Batdorf's shear-sensitive and shear-insensitive crack concepts are applied to randomly distributed volume flaws in macroscopically isotropic solids. Penny-shaped cracks and Griffith cracks are included in the shear-sensitive crack response calculations in conjunction with a choice of the following fracture criteria: Griffith's maximum tensile stress, critical coplanar strain-energy release rate, maximum tangential stress, and minimum strain-energy density. Three-dimensional finite-element analysis is applied to compute the element temperature, volume, and stress field necessary for the reliability distribution calculations.

Planned enhancements include multiple flaw distribution modeling, censored data analysis for material characterization, the establishment of confidence intervals, and the development of life prediction capability or time-dependent reliability analysis. Software capability will be expanded to include reliability analysis of ceramic composite materials such as a ceramic matrix reinforced with either ceramic whiskers or ceramic fibers.

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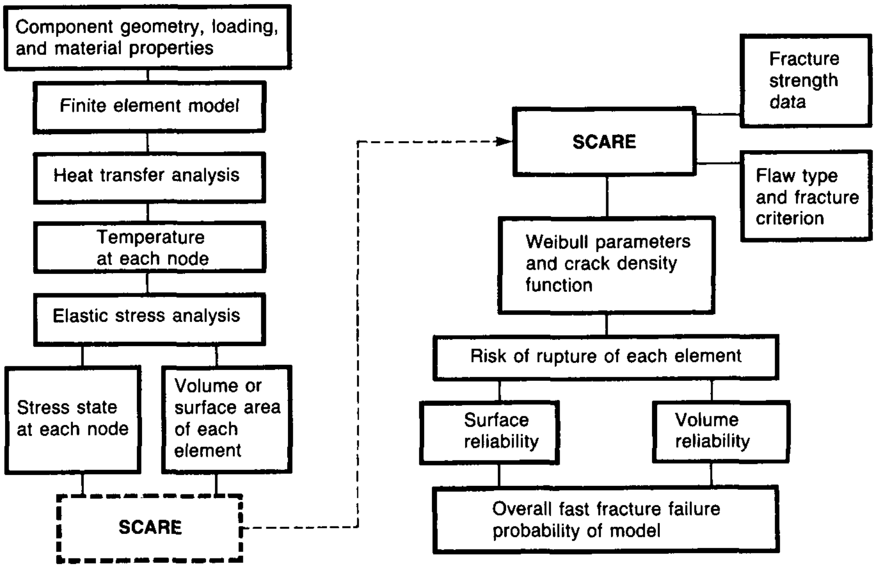

SCARE procedural diagram

Space Propulsion Technology

Triboelectric Flowmeter

Real-time liquid flow measurements are typically performed by turbine or venturi flowmeters. Such instruments are intrusive, cause pressure drops, and in case of failure can damage downstream components. The triboelectric flowmeter is an all-electronic, nonintrusive device that causes no changes to the flow stream.

As a liquid flows within a pipe, a naturally occurring frictional, or "tribo" electric charge is generated within the fluid. In a triboelectric flowmeter this charge, which is randomly distributed in the fluid, is monitored by a pair of electrodes embedded in the pipe at a known separation distance. A cross correlator analyzes the signals from the electrodes to determine the transit time for a charge distribution to move from the upstream to the downstream electrode. Mass flow may be determined from this time measurement and the known distance between electrodes, the fluid density, and the flow area.

Lewis is supporting research to develop a triboelectric flowmeter for use with cryogens. Under an initial contract it was determined that flowing streams of cryogenic fluids generate a measurable amount of triboelectric charge whose signals can be correlated with flow rate. Lewis has contracted for the construction of a prototype triboelectric flowmeter for use with liquid oxygen, liquid hydrogen, and liquid nitrogen. The intended application for this device is to measure the flow of cryogenic propellants in rocket engines such as the space shuttle main engine. Eventually this sensor could be incorporated into an engine diagnostic and control system to monitor engine conditions and to control engine operation. Such a system would improved engine safety, reliability, and cost effectiveness.

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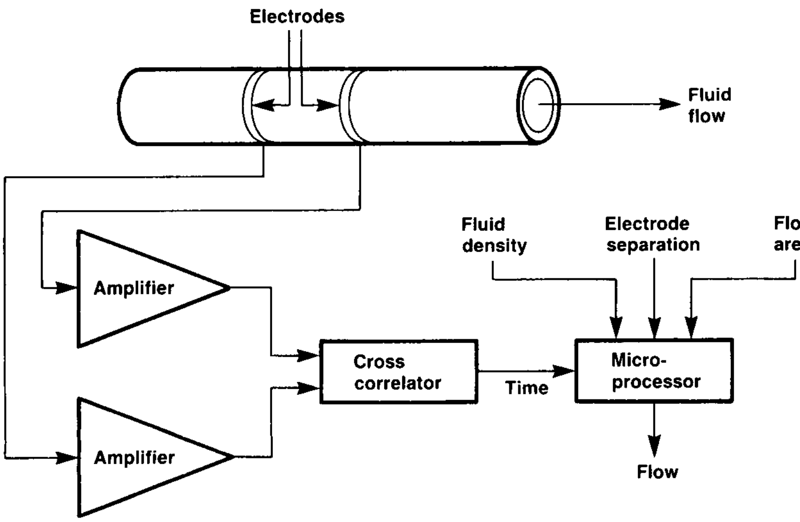

Triboelectric flowmeter

Capacitive Pressure Transducer

Pressure transducers used in rocket engine applications are exposed to large temperature extremes during normal operation. Therefore the output signals must be temperature compensated to yield accurate pressure information. Lewis-supported new technology is becoming available that will provide a pressure transducer with a low temperature coefficient that requires little or no compensation.

A Lewis-contracted investigation to evaluate a silicon chip constructed for use as a capacitive pressure transducer has been completed. The silicon chip has a micro-machined pressure diaphragm that functions as one plate of a capacitor and a cover glass with a vapor-deposited active electrode that acts as the second plate. Several bonding methods for the glass-to-chip attachment and several annealing methods for stress relieving the glass were tested at −150 to 150 °C. This transducer gives consistent performance with little temperature effect.

Lewis has begun a follow-on effort to provide a prototype pressure transducer for validation in the space shuttle main engine testbed being put in place at the Marshall Space Flight Center.

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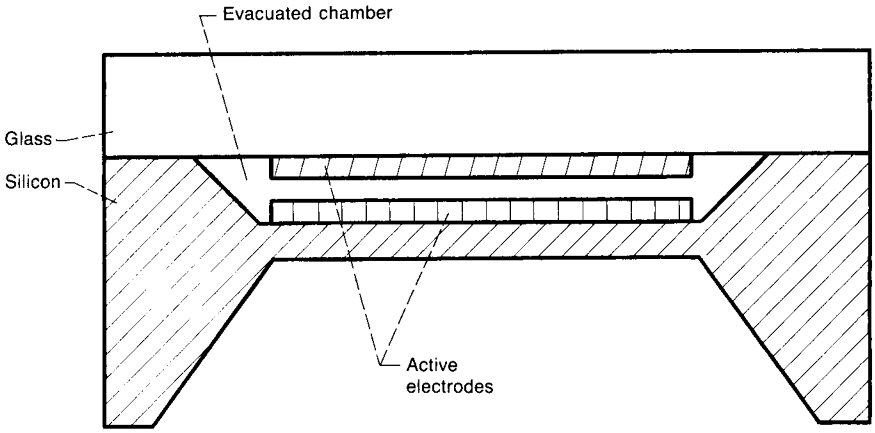

Cross section of capacitive pressure transducer

Long-Life, Liquid-Lubricated Cryogenic Bearings

The mean time between overhauls of the space shuttle main engine (SSME) is constrained by the limited life of the rotor support bearing in the high-pressure oxidizer turbopump (HPOTP). In response, Lewis has begun an in-house program to develop a direct retrofit bearing with longer life. A bearing analysis code that simulates the thermomechanical performance of a load support system was used to model the HPOTP bearings. The analysis showed that bearing life could be extended through changes in bearing geometry and bearing material as well as in the cooling and lubricating schemes.

The lubricating scheme is of particular interest for its life-extending potential. Solid lubricant is presently used in these bearings because conventional liquid lubricants, although more effective, solidify at cryogenic temperatures. However, Lewis has identified several fluorinated ethers that have good liquid lubricating characteristics at cryogenic temperatures. To extend bearing life, a liquid lubricating film must be maintained between the contacting surfaces of the bearing. Maintaining a protective film is difficult in the HPOTP environment, where the liquid oxygen used to cool the bearings washes away any lubricating film. Therefore an effective method of distributing the liquid lubricant to the contacting surface on the balls is essential.

Methods of liquid lubricant distribution, along with the other optimized parameters, will be tested under SSME conditions. In the first series of tests the liquid lubricant will be impregnated into the porous bearing separator. Although the contact that the cage makes with the balls effectively distributes the lubricant, the limited volume of the separator limits the useful life of this lubricating system. Therefore a replenishing system must be devised and tested. Several techniques are being considered; the most promising is a wick-fed system, where the wick is in contact with the balls and a reservoir of liquid lubricant.

Liquid lubrication, along with the other optimized parameters, will extend bearing life, lengthen service intervals, shorten flight turnaround, and lower maintenance costs. The program will benefit not only the SSME but all systems presently or potentially using bearings in a cryogenic environment.

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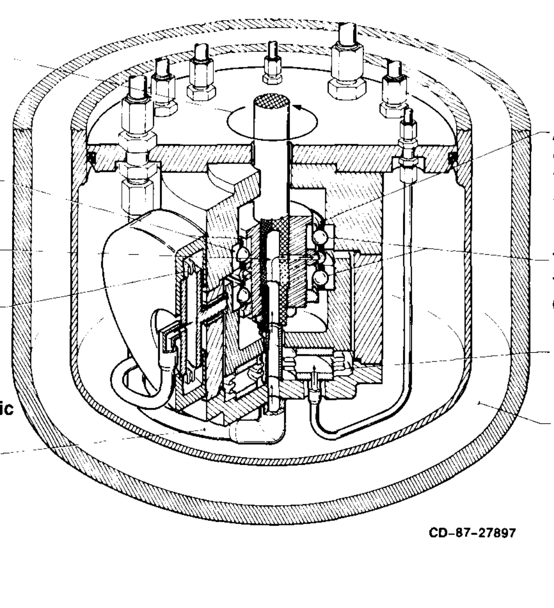


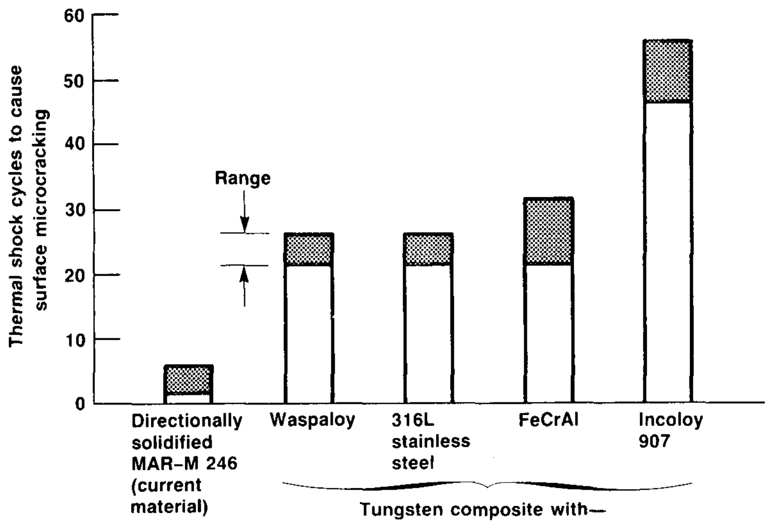
Rig for screening SSME turbopump bearing lubrication and cooling candidates

Fiber-Reinforced Superalloys for Reusable Rocket Engine Turbine Components

Significant advances in turbine blade material technology will be necessary for the next generation of liquid-propellant rocket engines. Tungsten-fiber-reinforced superalloy (FRS) composites show excellent promise for meeting these demanding design requirements. Preliminary studies indicated that FRS composites are uniquely suited for turbine blades in reusable rocket engines (e.g., the space shuttle main engines), where they may significantly extend blade operating life and temperature.

Rocketdyne, under contract to Lewis, recently completed an effort to experimentally confirm the key engineering properties of FRS components. Four candidate materials were fabricated at Lewis for evaluation by the contractor: 40 vol % tungsten–1.5 vol % thoria wire in either a iron-chromium-aluminum, Waspaloy, Incoloy 907, or type 316L stainless steel matrix. The testing demonstrated that the candidate FRS composite materials possess a highly attractive combination of properties for turbine blade applications in advanced rocket engine turbopumps. FRS blades are more durable and reliable because of their greater fatigue life and excellent resistance to thermal shock, hydrogen environmental embrittlement, and surface crack fatigue. Higher engine performance is also possible with FRS materials because the engine can be operated at higher temperatures.

Thermal shock resistance of current SSME blade material and tungsten-fiber-reinforced superalloys



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Hydrostatic Bearings for Orbital Transfer Vehicle Liquid-Oxygen Turbopump

Bearing life requirements for the orbital transfer vehicle (OTV) rocket engine exceed the capabilities of rolling-element bearings. Hydrostatic bearings, which float the shaft on a fluid film, have no metal-to-metal contact during normal operation and thus have longer life. In addition, hydrostatic bearings have higher stiffness. For these reasons Aerojet TechSystems Company has selected hydrostatic bearings for use in their liquid-oxygen turbopump for the OTV rocket engine.

In their turbopump design Aerojet combines the sealing functions with the bearing since hydrostatic bearings operate at close clearance (0.001 in.). The resulting parasitic leakage is less than that of conventional wear ring seals. Also, by combining a stiff rotor with the stiff hydrostatic bearing, operating speeds can be kept below the first critical speed. This reduces vibrational deflections that could close the clearance and cause a rub.

Two hydrostatic bearings are used in the liquid-oxygen turbopump. One is a journal bearing that supports the turbine end of the shaft. The other is both a journal and thrust bearing located between the two back-to-back pump stages. The thrust bearing acts on both pump stages. Both bearings have spherical seatings that allow the bearings to align themselves. To ensure ease of alignment, the spherical seats are also hydrostatic bearings operating at very close clearance (0.00001 in.).

Liquid-nitrogen testing of the hydrostatic bearings to be used in a liquid-oxygen turbopump has been successfully completed. Speeds of 72,000 rpm were obtained at 3200-psi bearing inlet pressure. The shaft spun freely and post-test examination found no evidence of wear. Parametric testing was done over a range of bearing inlet pressures from 20 to 3200 psi and speeds from 0 to 72,000 rpm. Displacement probes were used to measure the dynamic stability of the unloaded shaft. No instabilities were found over the range of operation. Testing will continue with the full turbopump configuration and liquid oxygen in the bearings. The performance of the impellers and the turbine will also be evaluated.

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Hydrostatic bearings

Two-Stage Partial Admission Turbine

Advanced hydrogen-oxygen, expander-cycle rocket engine concepts being studied for use in orbital transfer vehicles use partial admission turbines as the power source for both the oxygen pump and the hydrogen pump. The oxygen pump turbine is a single-stage design similar to configurations for which analytical codes have been experimentally verified. For the hydrogen feed system a two-stage partial admission turbine was shown by analyses to provide the highest efficiency. However, a lack of substantiating empirical data to support the analyses flagged the concept as a technology issue, and a contracted effort with Rocketdyne was conducted to determine performance and to establish a data base for future design.

Program scope consisted of design, fabrication, and laboratory testing of three two-stage partial admission turbine configurations with ambient-temperature nitrogen gas as the test fluid. The turbines had a 3-in. mean diameter and used rotors and an exhaust housing provided by Rocketdyne. Flow passages in the first- and second-stage nozzles could be individually blocked to change the degree of admission for a given test configuration. In addition, the second-stage nozzle could be circumferentially rotated during a given test to determine the effects of its nozzle angular orientation on turbine performance.

Completion of the program has made available a comprehensive data base for the design of two-stage partial admission turbines. The test configurations were generally more efficient than predicted with the unverified analysis codes. Varying the nozzle arc of admission produced generally expected trends, with the lowest performance coincident with the lowest arc of admission. Both efficiency and flow rate were sensitive to the circumferential position of the second-stage nozzle. The sensitivity increased as turbine arc of admission was decreased.

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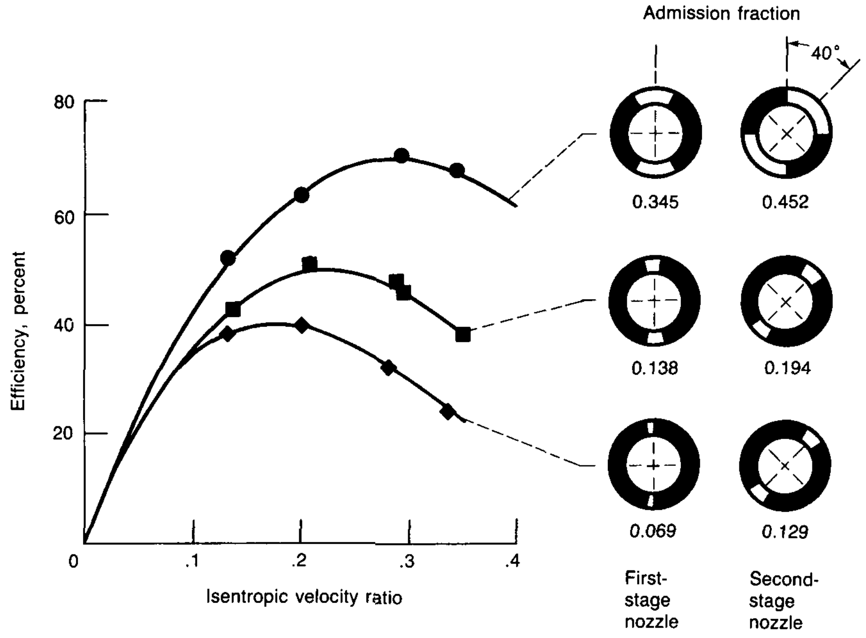

Effect of admission on efficiency

Low-Power Arcjet Technology

Low-power dc arcjets are being developed to replace the electrothermal thrusters currently used for auxiliary propulsion on communications satellites. The arcjet has recently proved capable of providing a specific impulse of 400 to 500 sec with hydrazine propellant.

In the arcjet an arc is struck between a tipped cathode and an anode that also acts as the nozzle and heats the propellant. A swirling flow of propellant is used to stabilize the arc gas dynamically. This vortex flowfield forces the arc to attach at the cathode tip and promotes diffuse attachment in the diverging section of the anode/nozzle. Keeping the anode attachment out of the high-pressure region upstream of the nozzle throat makes the heat load manageable and allows propellant temperatures not attainable with conventional resistive heating elements.

This ongoing research effort has produced arcjet thrusters that operate stably over a wide range of mass flow rate at power levels available to auxiliary propulsion systems. A power-processing unit has been developed that includes a fast-pulsed starting circuit and rapid current regulation. Most work to date has used the decomposition products of hydrazine as the propellant to take advantage of existing, space-qualified hardware. Starting reliability has been demonstrated and a 100-hr life test has been successfully concluded. Langmuir probe studies of the exhaust plume have been performed and these, along with studies of electromagnetic interference and transmission through the plume, will be continued to assess how arcjet systems affect spacecraft communications. Alternative propellants have been examined for applications requiring higher performance. Ammonia has been run, stably, for the first time, and specific impulses well in excess of 1000 sec have been obtained with hydrogen.

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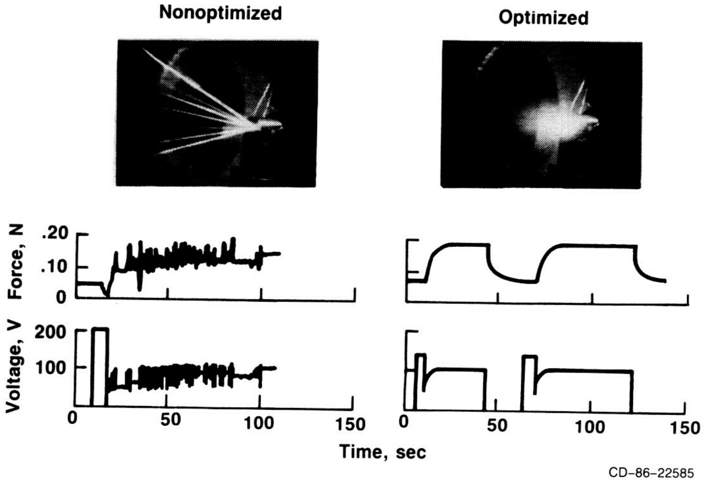

Reliable, nondamaging arcjet startup by optimization of flowfields, power circuits, and geometry

Demonstration of Superior Monopropellant Thruster Life

Attitude control and reboost are necessary for any spacecraft in low Earth orbit (150 to 200 miles in altitude) to keep it properly oriented and to compensate for orbit decay. Lewis is conducting a monopropellant thruster program to develop the technology for a small propulsion system that will perform for 10 years in space. In an effort to achieve this goal a new impulse record for a 5-lbf monopropellant thruster was set recently during successful in-house ground testing at Lewis. The tests were conducted over a 6-week period in a vacuum test facility that simulated duty cycles for space station attitude control and reboost on orbit. Key to the improved performance is a unique torsional spring retention system that maintains a tightly packed catalyst bed throughout the life of the thruster. The results are smoother operation and extended life.

The 5-lbf thruster was manufactured by the Rocket Research Company, a division of Olin Defense Systems, under a NASA technical exchange agreement. It achieved a total impulse of 1,084,000 lbf-sec and 216,800 sec of operation during testing at Lewis. No further tests are planned. In previous tests conducted by Rocket Research under an Air Force contract, one thruster was tested to 806,770 lbf-sec and a second was fired for 528,000 pulses.

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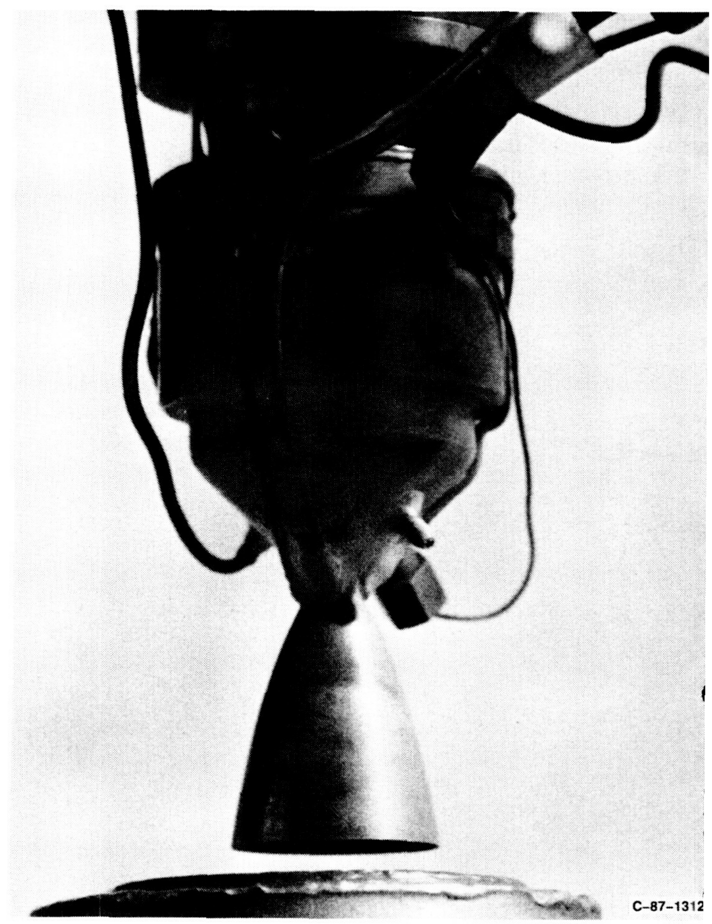

Monopropellant thruster

Small Hydrogen-Oxygen Thrusters for Space Station

The space station will require an auxiliary propulsion system capable of performing all the required propulsive functions including attitude control during free-flying and docking maneuvers, orbit raising, and collision avoidance. Studies have indicated the many potential benefits of 25-lb-thrust hydrogen-oxygen gaseous thrusters for the space station. Lewis thus began a program to design and build such thrusters and to verify their durability to ensure that the technology would be available for the initial space station.

Contract programs were conducted with Aerojet TechSystems and Bell Aerospace to design, build, and test such small thrusters for performance and durability. The Rocketdyne Division of the Rockwell Corporation also participated in this effort by supplying a small thruster from their independent research and development (IRAD) program. Studies of the space station and its environmental control and life support system have shown that a large synergistic benefit can be realized by using waste water as the propellant source. Hydrogen and oxygen are made available by electrolysis of this waste water. Therefore hydrogen-oxygen thrusters must be able to operate over a wide range of mixture ratios, but specifically long life must be ensured at a mixture ratio of 8, which arises from the electrolysis of water.

To verify the three thruster design concepts, performance tests were conducted at mixture ratios from 2 to 8. Significant test time was accumulated at mixture ratios near 8. The Aerojet and Bell thrusters accumulated total impulses greater than 430,000 and 225,000 lb-sec, respectively, at mixture ratios of 7 and 8. In extensive tests the Rocketdyne thruster attained a total impulse greater than 1 million lb-sec at mixture ratios near 4 and 1 million lb-sec at a mixture ratio of 8. This was the first time thrusters of this size had been so extensively tested for durability. None of the thrusters showed any distress or wear that would shorten their lives. Life estimates, based on measured temperature and calculated stress levels, are at the 20-million-lb-sec total impulse level.

This phase of the program has been completed, and small gaseous propellant oxygen-hydrogen thrusters of this size have been chosen as the baseline for the space station.

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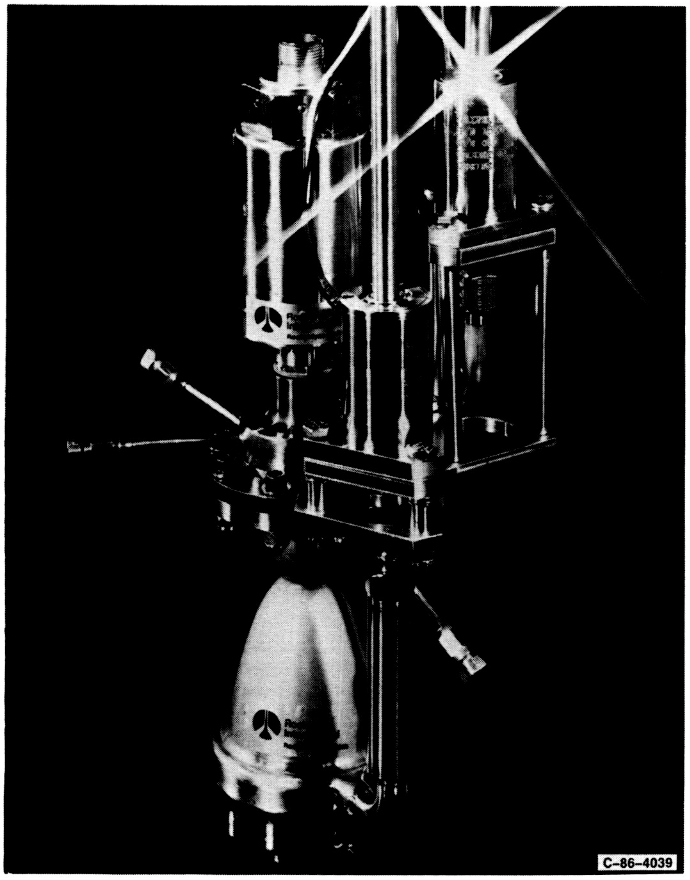

Flight type of hydrogen-oxygen thruster for space station

Testing of High-Area-Ratio Nozzles

Lewis is conducting a continuing investigation of the performance of high-area-ratio rocket nozzles. Nozzles with an expansion area ratio of 1030 have been test fired in the new altitude test chamber of the Lewis Rocket Engine Test Facility. These tests provided the first data that could be compared with analytical performance predictions for nozzles of this size. The performance of proposed orbital transfer vehicle configurations can now be projected with considerably improved confidence.

Testing is continuing at the facility, and boundary layer surveys are planned for comparison with analytical predictions. Studies to further define the laminar-to-turbulent transition and the laminarization of the boundary layer are in progress.

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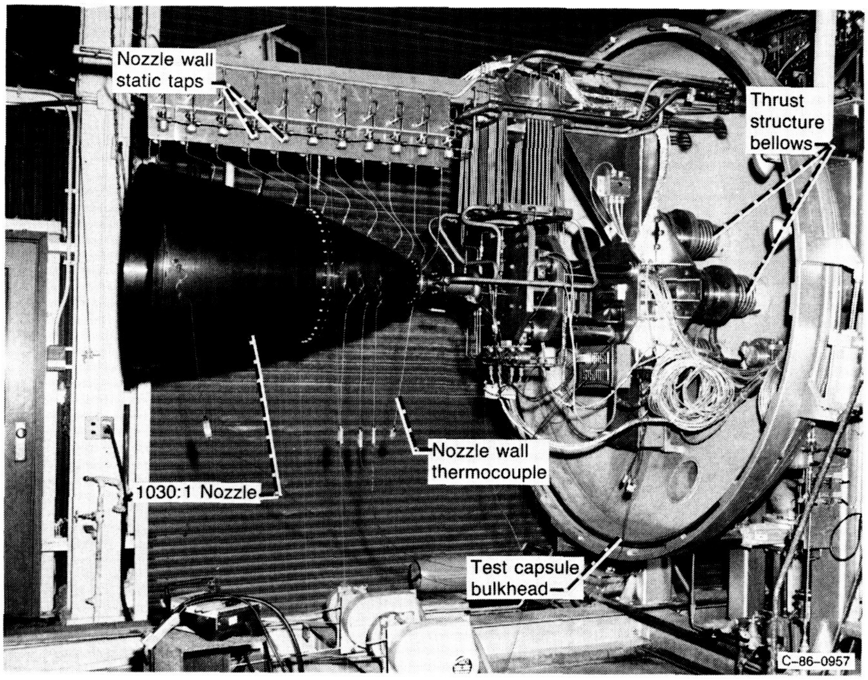
High-area-ratio nozzle on test stand

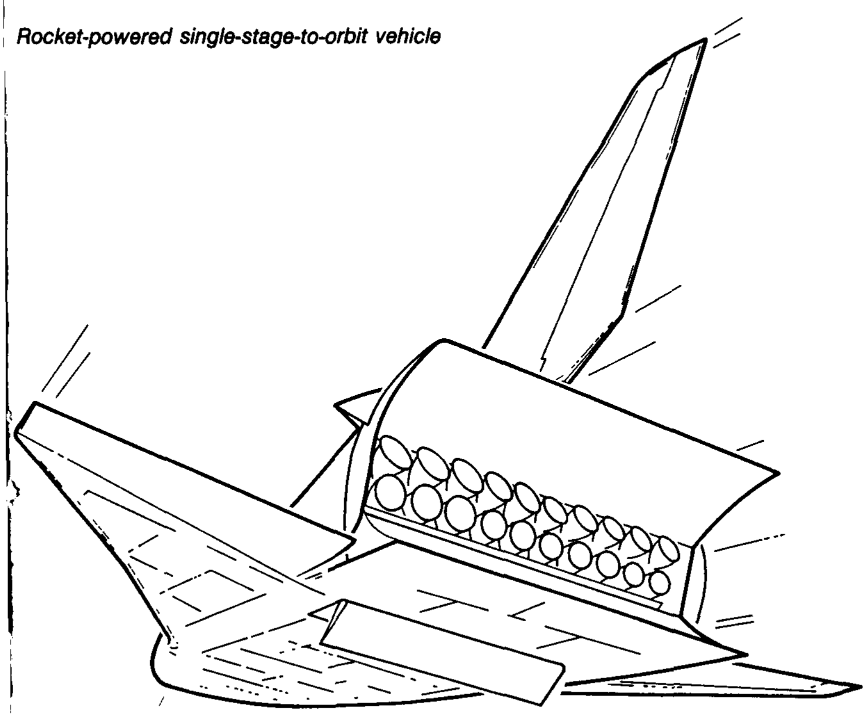


Rocket-Powered Single-Stage-to-Orbit Vehicle

Economical, high-performance launch vehicles will be needed in the 21st century to provide flexible, routine access to Earth orbit for passengers and high-value cargo. A completely reusable, rocket-powered single-stage-to-orbit vehicle could satisfy this need and significantly reduce the cost of achieving orbit by operating at a low level of logistical and operational support. However, advanced high-energy rocket propellants will be required for a single-stage-to-orbit rocket launch vehicle with a high payload-to-lift-off mass ratio. Metalized rocket propellants offer higher specific impulse and greater propellant density than more conventional rocket propellants. Therefore Lewis is evaluating the potential performance advantages of metalized propellants for a single-stage-to-orbit vehicle.

Thermochemical calculations were made to evaluate the theoretical rocket performance for a wide range of metal and liquid bipropellant combinations. Adding aluminum to the liquid bipropellants significantly improved specific impulse in several cases. Mission studies were then conducted to determine the improvements in vehicle performance derived from burning aluminum metal with conventional storable and hydrocarbon rocket bipropellants in a rocket-powered single-stage-to-orbit vehicle. Adding high-energy, high-density aluminum to certain liquid bipropellants increased delivered payload capability fourfold. In-house tests have begun to explore critical technologies and to further evaluate the potential of metalized propellants for this application.

Rocket-powered single-stage-to-orbit vehicle



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Hybrid Rockets for Advanced Earth-to-Orbit Boosters

Hybrid rockets offer the potential for greater safety and higher performance than solid-propellant rockets because they use a combination of solid and liquid propellants. Lewis is thus conducting in-house studies to explore the potential of hybrid rockets as replacements for the space shuttle solid rocket boosters and for other advanced Earth-to-orbit boosters. Initial studies have focused on one type of hybrid rocket called the quasi-hybrid rocket.

The quasi-hybrid rocket, a solid-propellant rocket augmented by liquid hydrogen, is named for its tendency to exhibit operational characteristics of both solid-propellant and conventional hybrid rockets. Theoretical rocket and vehicle parameters were calculated for several quasi-hybrid rocket configurations over a range of operating conditions. The results indicate that quasi-hybrid rockets offer large theoretical performance advantages over solid-propellant rockets. These performance advantages are somewhat limited in actual Earth-to-orbit booster applications because of constraints on vehicle size.

Despite their desirable performance quasi-hybrid rockets were determined to be an inappropriate choice for replacement of the space shuttle solid rocket boosters after several unique operational safety problems were identified. The studies are continuing with their focus on other types of hybrid rocket systems.

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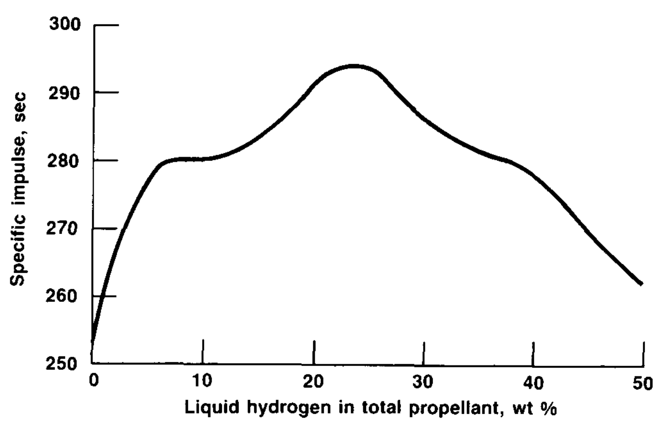
Performance of quasi-hybrid rocket



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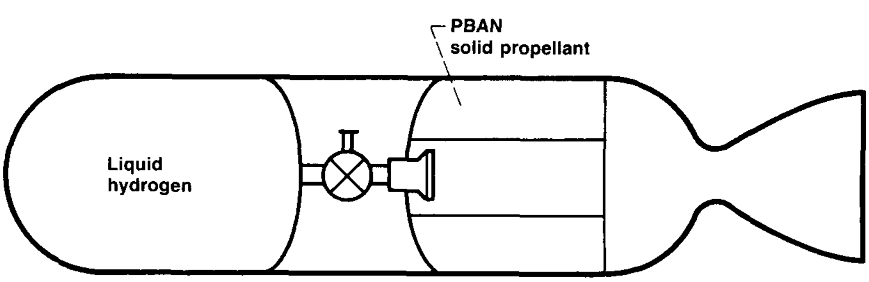

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Electrodynamic Tether Technology

A variety of propulsion and power generation applications have been identified for space tethers, which involve electrodynamic interactions of the tether wire with planetary magnetic fields. Electrodynamic tethers may offer significant advantages in space transportation and power generation in the near-Earth space environment by the 21st century by providing an extremely efficient means of conversion between electrical energy and spacecraft orbital kinetic energy. Lewis has been involved in an experimental assessment of plasma contacting devices to enable electrodynamic tether operation. Now this ongoing program has been expanded to evaluate the technical feasibility, operational risks, technology requirements, and overall costs and benefits of tether systems as compared with other existing and planned future technologies.

An experimental evaluation of plasma contactor operation, conducted in-house and at Colorado State University, has successfully developed a physical-mathematical model describing contactor performance. This model will facilitate the development of contactor devices for use in near-Earth space, where the ambient plasma density and conduction current conditions vary widely. This experimental program led to the development of preliminary plasma contactor designs that have demonstrated performance, in ground-based space simulations, sufficient for tether operation at power levels of 20 kW or higher.

A tether power and propulsion systems study and a study of plasma turbulence generated by tether current flows have been conducted by the Massachusetts Institute of Technology. Results from the systems study indicate that the electrodynamic tether is not competitive as a primary power generator, owing to its large specific mass, out-of-plane resonance, and growth in orbital eccentricity. However, the tether is attractive as an emergency power generation system and as a primary propulsion system. For near-Earth orbit transfers the tether may have performance capabilities—transfer time and payload delivery capability—competitive with those of refuelable solar electric propulsion systems. However, further tether propulsion studies are needed to quantify system benefits in detail.

A shift in the program emphasis toward development of theoretical and experimental bases required to support flight experiments has motivated other analytical efforts now under way to assess contactor and tether plasma interactions with spacecraft. Plasma contactor operation on the shuttle orbiter has been simulated by combining a one-dimensional model of hollow cathode plasma effluence with the three-dimensional NASCAP-LEO code. This provides calculated potential contours in the shuttle orbiter vicinity and values of ion current collected by the shuttle during contactor operation. Other studies include evaluation of spacecraft data on electron and ion beam interactions with the ambient ionospheric plasma as well an assessment of far-field circuit closure (return path) of the tether current through the ionosphere.

Lewis plasma contactor and tether flight experiments are presently being funded in the definition phase. These shuttle- and sounding-rocket-based experiments are being designed to provide engineering data by which to evaluate the feasibility of space tethers for propulsion and power generation applications.

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Selection of 50-cm-Diameter Ion Thrusters

High-specific-impulse ion thrusters, which are proposed for space propulsion, inherently have a low ratio of output thrust to input power. Since electric power in space has been limited, state-of-the-art ion thrusters are small in both size and power level. However, nuclear power sources can produce larger quantities of electricity (levels from 100 kW to multimegawatts are proposed), and efficient ion propulsion now appears attractive. When state-of-the-art thruster designs are applied to missions using space nuclear power systems, the number of thrusters becomes prohibitive. Therefore Lewis is conducting an in-house program to increase the power and thrust per thruster. One approach has been to augment the power and thrust densities of 30-cm-diameter thrusters. A second approach, based on the results of recent studies, is to increase the size to 50 cm in diameter. Combined, these two approaches can reduce the number of thrusters required by more than a factor of 10.

Two ion production chamber designs have been selected to be incorporated into 50-cm-diameter ion thrusters. The first design (research model) incorporates strong boundary magnetic fields, produced with rare-earth magnets, to efficiently contain the plasma produced. Preliminary test results with this design have validated its promise of scalability without multiple design iterations or loss of efficiency. The research model thruster is being tested with a 30-cm-diameter ion accelerating system. Full-size ion accelerating systems are being fabricated. The second ion production chamber design (laboratory model) will use electromagnets to produce a magnetic field that diverges, from the on-axis cathode region to the downstream accelerating system, over the discharge volume. This design, although not as efficient as the research model, has been developed to flight status in the Space Electric Rocket Test (SERT II), Ion Auxiliary Propulsion System (IAPS), and Solar Electric Propulsion System (SEPS) thrusters. Components are being fabricated, and assembled thrusters will be evaluated in fiscal 1988.

A baseline operating point has been selected and the expected initial performance values of the 50-cm-diameter ion thrusters are as follows: both the research and laboratory models will use xenon propellant and approximately 27 kW of power to produce 0.94-N thrust at 4710-sec specific impulse and approximately 80-percent efficiency. Reduced ion production power will reduce the required cathode emission current by approximately 50 percent and lower thruster temperatures.

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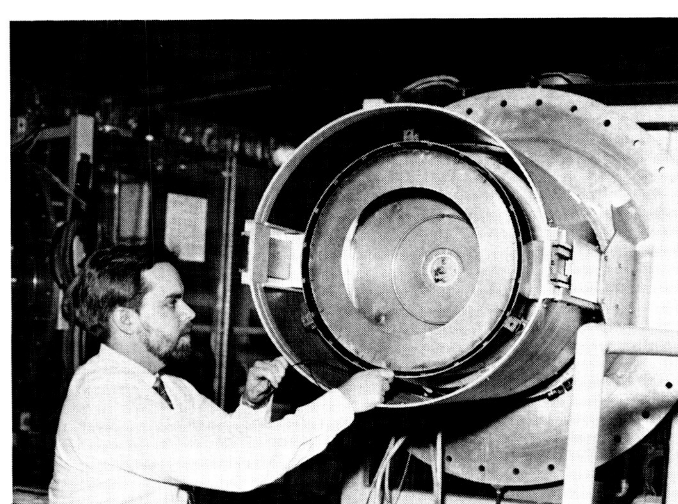

Research model thruster in 30-cm-diameter ion accelerating system

Compatibility of Dispersion-Strengthened Platinum With Resistojet Propellants

Resistojets for space station must have long life and multipropellant capability. The choice of available materials to meet these requirements is limited. Lewis selected dispersion-strengthened platinum for study and found it to be sufficiently inert in candidate propellant environments and capable of operating at moderate temperatures for extended times.

The compatibility of dispersion-strengthened platinum with potential space station resistojet propellants was evaluated in a series of 1000-hr tests. Platinum-yttria and platinum-zirconia were exposed at 20-psia chamber pressure to flowing gas environments of carbon dioxide, hydrogen, ammonia, nitrogen, steam, and hydrazine at 1400 °C, methane at 500 °C, and hydrazine at 800 °C. Tests for 2000 hr at 1400 °C in hydrogen and ammonia were also performed. The test sample and operating temperature were representative of a resistojet heating element.

The life estimates, extrapolated from the mass losses occurring in these tests, indicated that platinum-yttria and platinum-zirconia would withstand a minimum of 45 000 hr in any of the environments tested—greater than four times the expected space station life requirement. Grain growth is not considered a problem, but detailed analysis of any effects should be part of the final design in the intended application. Both platinums should be acceptable for space station resistojets using carbon dioxide, hydrogen, nitrogen, steam, and methane. Ammonia and hydrazine may also be acceptable propellants if the resistojet operating temperature is lowered below 1400 °C.

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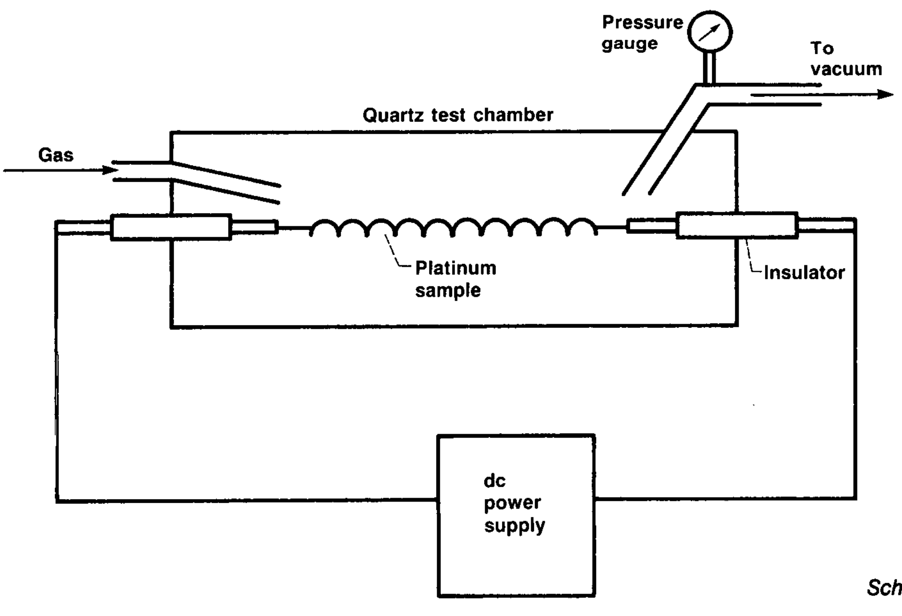

Schematic of resistojet material test cell

High-Temperature, Oxidation-Resistant Thrusters

Lewis is working to achieve an oxidation-resistant thrust chamber capable of operating at 2500 K (4000 °F). The state of the art is 1600 K (2400 °F) with fuel film cooling in small thrusters (5-lbf thrust). Bipropellant thrusters using nitrogen tetraoxide/monomethylhydrazine (NTO/MMH) should have at least 10 times the life and a 20 sec higher specific impulse.

The Lewis program is divided into three phases. The first phase, which has been completed, examined promising material system candidates—refractory metals, Engle-Brewer compounds, ceramics, cermets, and carbon-carbon—as substrates and coatings. The most promising candidates are rhenium coated with iridium and rhenium coated with iridium plus 50 percent rhodium.

The first of these thrust chamber material systems has recently been evaluated as a "workhorse" test chamber in the second phase of the program, consisting of hot fire and cyclic testing. A 5-lbf-thrust chamber was tested for an accumulated hot-fire time of 12 hr with NTO/MMH propellants. Testing consisted of 59 deep thermal cycles and 2670 pulses. Most of the testing was at a mixture ratio of 1.65, and the chamber temperature ranged from 3700 to 4100 °F. There was a very slight weight difference after testing but no measurable dimensional difference.

Additional testing in the second phase consisted of engineering evaluations of the other promising thrust chamber material system as well as several Engle-Brewer compounds.

The third phase of the program, just beginning, consists of design, fabrication, and testing of a testbed thrust chamber. Plans under consideration include testing with NTO/MMH, NTO/hydrazine, and hydrogen-oxygen.

This program is the first step in an advanced thruster technology program that responds to new space operations architectures including space system resupply and refurbishment.

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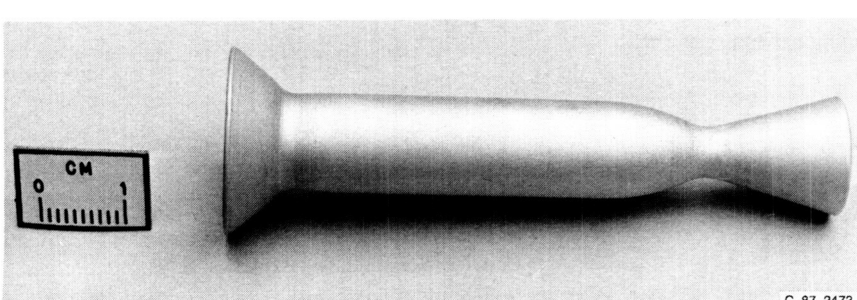

Oxidation-resistant thrust chamber

Microwave Thruster

Future space missions will employ large, high-power spacecraft and will require propulsion systems with high thrust and high thrust density. The microwave thruster concept appears to be able to satisfy the anticipated requirements of these missions. Microwave coupling to various propellant gases has proved to be an efficient process. At low power levels (<2.0 kW) energy efficiencies comparable to those of electrothermal propulsion devices have been demonstrated. Similar energy efficiencies should be achievable at substantially higher power levels (>10 kW). At these power levels the specific impulse attainable at a given thrust level from the microwave thruster should greatly exceed those available from chemical thrusters, resistojets, and so forth. The thrust densities attainable will be orders of magnitude greater than those from electrostatic ion thrusters. Compared with other electrothermal thruster concepts, the microwave thruster also offers the advantages of longer life, no internal electrodes, less stringent material requirements, propellant compatibility, and relative system simplicity.

The microwave thruster has been developed in a cooperative effort between Lewis and Michigan State University (MSU). Experimental and analytical studies are continuing at MSU. The experimental work at Lewis is intended to demonstrate the feasibility of extending microwave thruster operation to high power levels at frequencies and with propellants that are most advantageous for future space applications.

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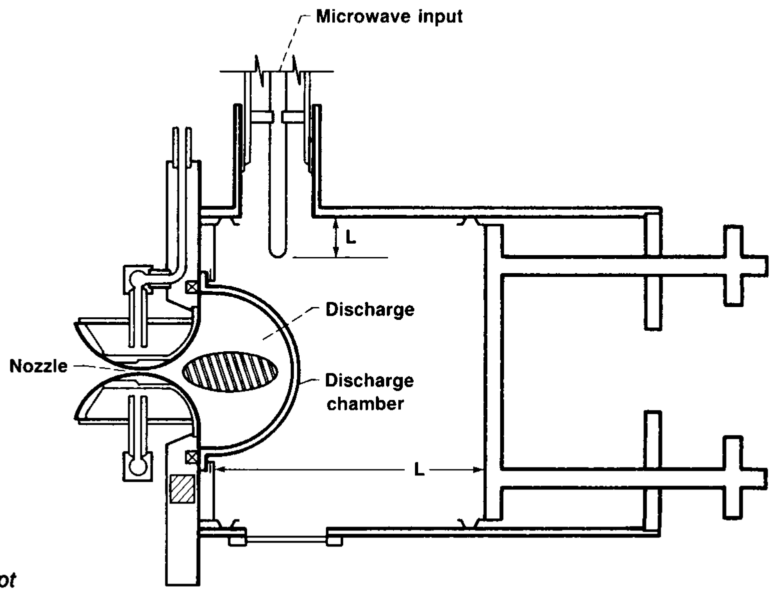

Microwave plasma thruster concept

Manned Mars Nuclear Electric Propulsion/ Ion Analysis

Current studies such as "Pioneering the Space Frontier" by the National Commission on Space have recommended manned exploration and settlement of Mars. The SP–100 nuclear-powered flight program has renewed interest in electric propulsion and stimulated work in high-power electric thrusters. Lewis is working to combine its expertise in space power and propulsion with detailed trajectory analysis capabilities in order to define both near-term and far-term missions to Mars.

An analytical study was conducted to determine trip time, system masses, and payload delivery capability to Mars for a nuclear electric propulsion system. Input power levels of 300 kW and 3 MW were used to study near-term and far-term missions, respectively. A 50-cm-diameter ion thruster system was modeled on the basis of 30-cm-diameter performance and on current 50-cm experimental work being performed at Lewis. Propellants studied included xenon and argon, with both low and high molecular weight propellants also being considered. Trajectory analysis was performed by using the computer code NBODY executed on the Cray XMP supercomputer.

Results indicate that a 50-cm-diameter ion propulsion system working at 300-kW input power can deliver sufficient payload to accomplish a sample-return mission or a robotic survey mission while requiring only one shuttle launch. The same ion propulsion system working at 3-MW input power can deliver a combination of heavier payloads such as habitat modules, power units, or heavy machinery. Technology issues include increasing the power processed per thruster in order to reduce the number of thrusters at the 3-MW power level.

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Power Technology

High-Capacity Power Conditioning and Control

Power requirements of future NASA missions are projected to increase dramatically. The initial space station will consume 75 kW of power, and the station's power system is being designed to accommodate its anticipated growth to 300 kW. A lunar base, or an electric rocket of the type needed for a manned sortie to Mars, will require megawatts of power. The power electronics program at Lewis seeks to provide the components and circuitry required to effectively control these large amounts of electric power and to condition the power to meet the needs of specific applications.

Work in this ongoing program is now being completed on a variety of 10- to 100-kW components that will form the basis for the space station electrical system. These include the roll-ring rotary power transfer device, the metal oxide semiconductor field effect transistor (MOSFET) controlled thyristor, a 20-kHz ac power transmission cable, and special lightweight capacitors and transformers. Current work is focused on three technology needs that are critical to future missions: the need for electronics that can operate at much higher temperatures, the need for electronics that can operate in the radiation fields produced by space nuclear reactors, and the need for fault-tolerant circuits. Individual projects within the program focus either on critical circuits such as inverters or on advancing the state of the art of components. Grants, contracts, in-house efforts, or combinations of them, are used as appropriate to perform the work.

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High-Efficiency Indium Phosphide Solar Cells

Indium phosphide solar cells are in an earlier stage of development than silicon and gallium arsenide cells. Silicon (Si) cells have been under development for 27 years; gallium arsenide (GaAs) cells, for 17 years; but indium phosphide (InP) cells for space use, for only 6 years. Despite this relatively short development time InP solar cells have been demonstrated to be significantly more radiation resistant and annealable than either GaAs or Si cells. Since InP cell efficiencies were initially relatively low, a major emphasis in the Lewis program has been toward developing a high-efficiency InP cell.

To date, the highest InP solar cell efficiency attained anywhere in the world, 18.8 percent, was measured at Lewis on a cell developed, under a Lewis contract, by the Spire Corporation. This high efficiency was achieved by combining ion implantation with metal organic chemical vapor deposition and careful substrate preselection in processing the cell. The present InP cell efficiencies surpass the 15 percent efficiency attainable with Si space cells and approach the 21 percent reported for GaAs. Furthermore laboratory data indicate that this InP cell can provide significantly more end-of-life output power in the space radiation environment.

Current efforts are directed at producing an InP cell capable of reaching theoretical efficiencies greater than 20 percent. Future efforts will be directed toward reducing cell costs and producing a manufacturable InP cell. The resultant cell is expected to be superior to any of the cells currently used in space.

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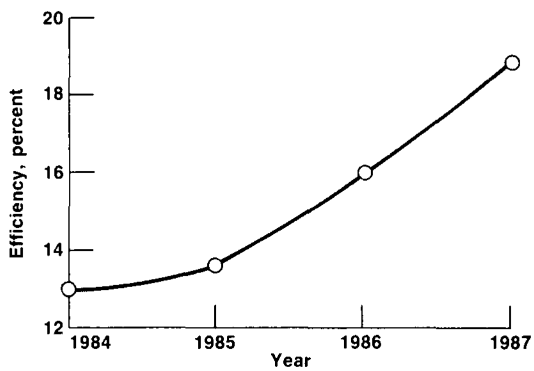

Progress in achieving high-efficiency indium phosphide solar cells

Separators for Nickel-Hydrogen Space Batteries

Separator technology is a critical element in the nickel-hydrogen battery system. Battery performance depends largely on the separator material characteristics. The separator is also an integral part of the design. Its pore size distributions play an important role in electrolyte management. As part of the development program to improve nickel-hydrogen systems for future applications in low Earth orbit (LEO), such as space station, Lewis undertook a separator development program. Its goal was to develop a separator that would resist penetration by oxygen as well as by loose active material, would be chemically and thermally stable, and would have high reservoir capability and high ionic conductivity.

State-of-the-art separators are manufactured from asbestos or zirconium dioxide cloth. Deficiencies associated with both separators, such as availability, potential health hazards, and electrolyte distribution, led to the Lewis development program, which has involved a broad range of research and development—from fiber and material capability to the development process for the final separator.

In-house research demonstrated the performance of replacement separators made of potassium titanate and zirconium dioxide fibers. Cell voltages were good and midpoint voltages were even higher than those for asbestos. These separators were manufactured manually on a Williams sheet mold at low production rates. To demonstrate the feasibility of using the new separators in a variety of applications, it was necessary to produce larger sheets at higher rates. In an effort to bridge the gap between handmade sheets and commerical production, a program was put into effect with the Paper Science and Engineering Department of Miami University of Ohio. This effort identified polyethylene as a fiber that could also be used in these separators. The capability of manufacturing new separators has been demonstrated, and the process of optimization has begun so that the desired properties can be obtained reliably and reproducibly as required for any flight product. The successful development of these separators, as replacements for asbestos, may ultimately make possible the use of advanced designs in nickel-hydrogen battery systems for future NASA missions.

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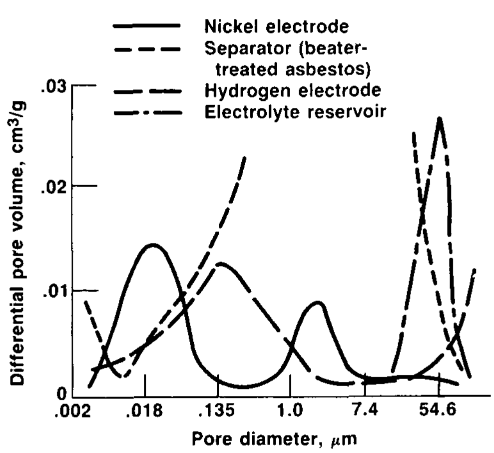

Differential separator pore volume versus pore diameter

Breakthrough in Cycle Life of Individual-Pressure-Vessel Nickel-Hydrogen Cells

The nickel electrode effort is part of an overall program to advance the technology of nickel-hydrogen cells and batteries for use in energy storage systems for space power in low Earth orbit (LEO). The nickel electrode is the life-limiting component of state-of-the-art individual-pressure-vessel (IPV) nickel-hydrogen cells cycled at deep depths of discharge (DOD) under a LEO cycle regime.

A contract was awarded to Hughes Aircraft Company to extend the life of the nickel electrode cycled in nickel-hydrogen cells (LEO; 80 percent DOD). This contract produced a nickel electrode failure model which predicted that decreasing nickel electrode expansion would extend cycle life. One possible way of doing this would be to decrease the potassium hydroxide (KOH) electrolyte concentration. It has been reported by others, from work done on nickel-cadmium batteries, that the KOH concentration affects the nickel electrode expansion. However, the main failure mode in nickel-cadmium batteries is not due to the nickel electrode. One task under the Hughes contract was to investigate the effect of KOH electrolyte concentration on the cycle life of nickel-hydrogen cells. The KOH concentrations used in boilerplate cells were 21, 26, 31, and 36 percent. State-of-the-art nickel-hydrogen cells currently use 31 percent KOH.

The results to date of this investigation have shown that the cycle life of the nickel electrode lengthened significantly as the KOH concentration decreased, although the initial capacity did decrease slightly. Cycle life lengthened by at least a factor of 10 (to 33 000 cycles) when the KOH concentration was reduced from 31 percent to 26 percent. This breakthrough in cycle life results in a superior IPV nickel-hydrogen cell that makes possible significant agency missions such as space station and space platform.

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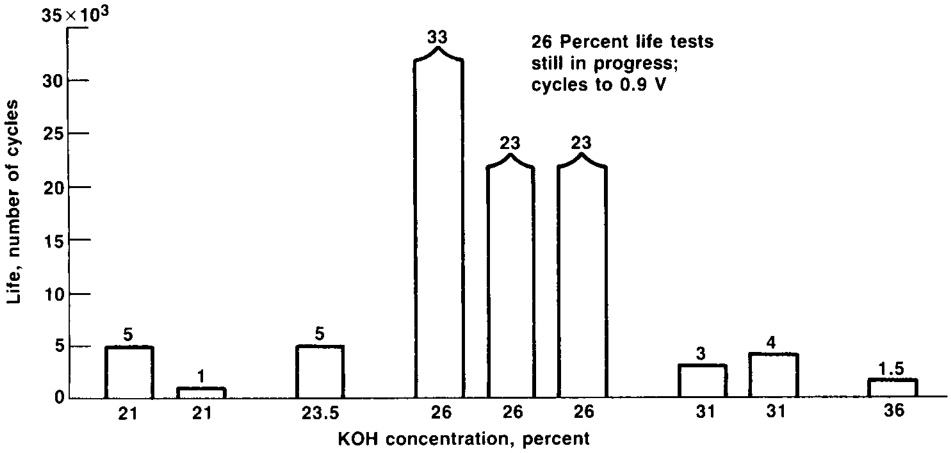

Cycle life of nickel-hydrogen boilerplate cells with various KOH concentrations

Neutron Tolerance of Deep-Impurity, Double-Injection Switches

In addition to a gigarad tolerance to gamma irradiation the new family of semiconductor switches based on deep-impurity, double-injection $(DI)^2$ techniques in silicon have demonstrated a tolerance to fast neutrons up to a fluence of 10^{15} neutrons/cm^2. These semiconductors are being developed and modeled under a grant to the University of Cincinnati and studied under contract by Westinghouse Research Laboratories and have been studied for radiation hardness and high-temperature effects under a grant to Hampden-Sydney College. Eight pairs of unmounted, diced switching devices prepared from a silicon wafer of 64 Ω-cm initial resistivity with compensated gold as the deep impurity were irradiated with fast neutrons at fluences from 10^{13} to 10^{16} neutrons/cm^2. Results show some deterioration in the current-versus-voltage and switching-time-versus-voltage characteristics to 10^{15} neutrons/cm^2. At 10^{16} neutrons/cm^2, however, degradation was sufficient to render the devices unusable, although total device failure had not yet occurred.

New device models with zinc rather than gold as the deep impurity show a potential factor-of-10 improvement (to 250) in the ratio of threshold to holding voltage. When demonstrated experimentally in the ongoing program, this will significantly enhance the switching efficiency and lower both conduction losses and off-state leakage currents. Radiation-hard semiconductors are critical elements for electronic control, sensing, and power conversion at or near nuclear reactors. This capability would dramatically reduce component and shielding weight and heat rejection problems associated with multikilowatt- and megawatt-level electric power generation, conversion, and distribution systems in space.

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Power System Autonomy Project: 1990 Demonstration

Lewis has been selected to develop the required advanced autonomy technologies on a 20-kHz power system testbed to coordinate with a thermal control system at Johnson Space Center in a 1990 demonstration of the automated control of the two subsystems. This demonstration is the second phase of the Systems Autonomy Demonstration Project (SADP), a major component of NASA's Automation and Robotics Program. The goal of SADP, managed through Ames Research Center, is to demonstrate advanced automation technologies by applying expert systems and artificial intelligence technologies to space systems in order to enhance their autonomous operation. Selected advanced automation technologies will be developed and applied to some space station systems to increase their reliability, safety, and payload capability and to decrease their operational costs.

Of significance in Lewis' role is the cooperation between the Space Station Directorate and the Aerospace Technology Directorate so that the required knowledge base and advanced automation controllers can be developed directly on space station power system testbeds. Limited staff and funds are thus made more productive by immediate data flow into a knowledge base and expert system technology development effort. The acquisition of operational expertise ensures maximum applications of advanced automation technologies on the initial-operating-capability space station and subsequent NASA missions.

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Nuclear Reactor Power System Concepts for NASA Growth Space Station

Lewis is assessing the feasibility of installing, operating, and disposing of several types of nuclear power systems that may be applicable to the projected 300-kW growth version of the proposed NASA space station. Three power system configurations—a single tether mount, a single boom mount, and a dual boom mount—were selected for detailed examination. Integration, operation, and safety issues associated with their installation, separation, and end-of-life disposal were studied. Propulsive energy requirements and characteristics were identified for six potential final disposal destinations, which ranged from a long-life Earth orbit to a solar system escape trajectory. A variety of expendable chemical (both cryogenic and storable) upper stage vehicles were studied to identify their operational characteristics. Also, a matrix of propulsion system components and reactor system payload combinations was evaluated to identify potential disposal, integration, and nuclear safety issues.

This assessment has confirmed the feasibility of the nuclear concepts investigated. All the concepts were found to be compatible with boost to safe 1000-km Earth orbits at end of life with any existing chemical propulsion, shuttle-compatible upper stages. For this disposal destination the solid-rocket-motor, payload-assist-module upper stage should be integrated with the nuclear power system after reactor shutdown. Should higher energy disposal destinations be required, Earth-escape elliptical solar orbit is the preferred mode. Although the propulsive energy requirement is more than an order of magnitude greater than that required for a 1000-km Earth orbit, it can be achieved by the lightweight tether mount configuration with an appropriate shuttle-compatible upper stage vehicle placed in low Earth orbit with a single launch.

However, all the reactor power systems are capable of boost to Earth escape with propulsion systems that are integrated in space following separate launches of propellant and upper stage hardware. This scenario, which involves pumped liquid propellant transfer after reactor shutdown, was found to be the most attractive from a payload integration aspect.
Although propellant mass requirements are reduced by about 35 percent with cryogenic hydrogen-oxygen upper stage vehicles, the synergistic operational benefits associated with the use of water (which can be electrolyzed to produce hydrogen and oxygen) in the space station may significantly affect propellant selection. In general, no insurmountable technical barriers to feasibility have been identified, and only modest technology advances and major requirements definition are needed to verify concepts and resolve open issues.

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Electric Utility Application of Phosphoric Acid Fuel Cells

A major element of the Lewis Phosphoric Acid Fuel Cell Project for the U.S. Department of Energy is the Westinghouse Electric Corporation technology development effort, carried out principally under a 9-year multimillion dollar contract. Advanced technology in this contract effort has progressed significantly during the past year from laboratory models to full-size units. A basic building block, 32-kW air-cooled fuel cell stack has been successfully designed, assembled, and tested.

The concept was further demonstrated with the successful operation of a 100-kW stack consisting of three 32-kW stacks placed one above the other and operated as an integral unit. The stack produced 112.5 kW of dc power while operating on synthetic reformed gas under pressure at powerplant conditions (70 psia, 267 mA/cm^2, 190 °C, and 83/50 fuel/air utilization).

This ongoing project paves the way to building and testing a 375-kW powerplant module by clustering four 100-kW stacks in a single pressure vessel. Four modules will be built and tested in a 1.5-MW pilot powerplant before a 7.5-MW demonstration powerplant is built.

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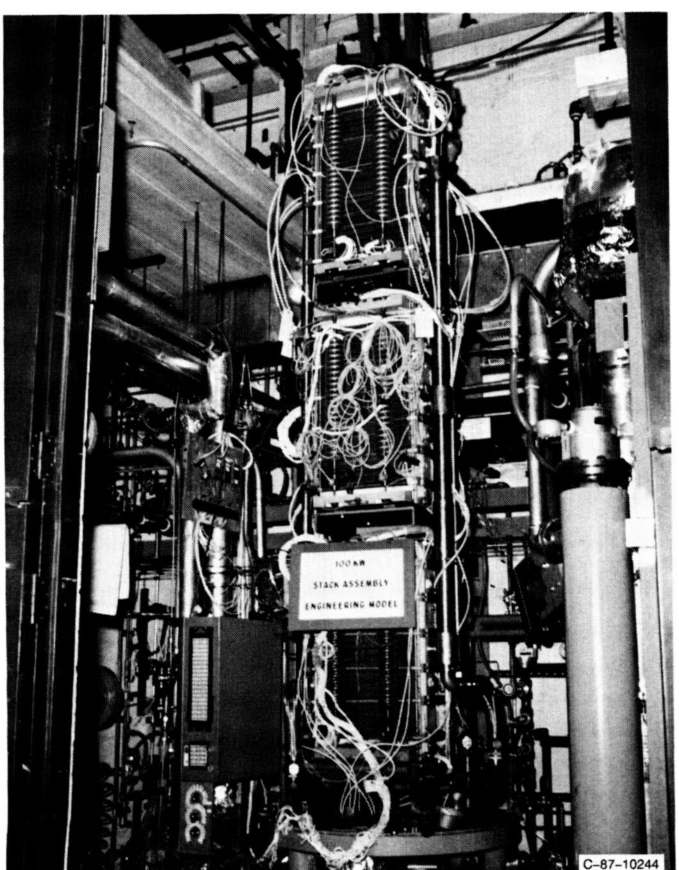
Funding source, DOE



100-kW stack assembly

On-Site Phosphoric Acid Fuel Cell Technology

The International Fuel Cells effort to develop the technology for an on-site phosphoric acid fuel cell (PAFC) powerplant, another major element of the Lewis PAFC project for the U.S. Department of Energy, is nearing successful completion. Final verification of on-site PAFC technology, where the powerplant is located in close proximity to the user, is under way with the test of a 30-cell short stack and a breadboard 200-kW powerplant designated the "verification test article" (VTA).

The short stack, constructed with cells of the baseline design for the on-site, 200-kW commercial prototype powerplant, has been tested for 1100 hr (as of June 1987). Its performance was 10 mV above the program goal at a current density of 365 A/ft^2, and the decay with time followed the projected decay characteristic. This successful operation demonstrated the performance potential and viability of using the low-cost materials and fabrication techniques inherent in the commercial baseline configuration.

The VTA comprises a 200-kW stack, a fuel processor, a thermal management system, a water treatment system, and appropriate powerplant controls. These subsystems have been fabricated and checked out. The VTA has been assembled and testing has begun. After a smooth startup test the VTA now is being operated as a closed loop. A successful VTA will provide valuable data on the performance and interaction of the major subsystems of the commercial 200-kW powerplant.

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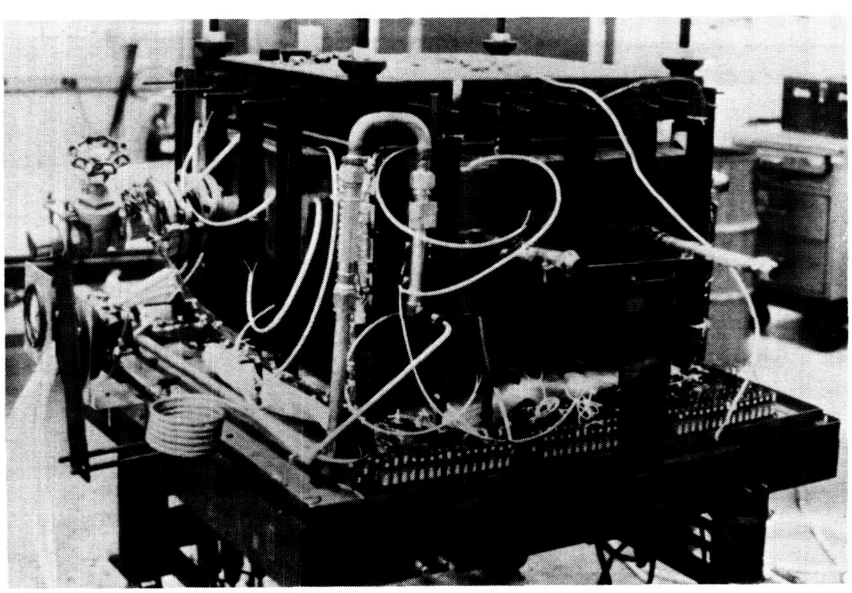
Funding source, DOE



30-Cell development stack

Mathematical Treatment of Current Density Distribution in Solid-Oxide Fuel Cells

Working on-site under contract to Lewis, a Cleveland State University research associate has developed two generic engineering models for calculating the current density distributions of the Westinghouse tubular and Argonne National Laboratory (ANL) monolithic cross-flow solid-oxide fuel cells (SOFC). Two-dimensional current density profiles (circumferential and axial for the Westinghouse cell and planar for the ANL cell) were calculated at an isothermal condition (1000 °C). Current density was nonuniform along the axis and around the circumference of the tubular cell. For a 0.275-A/cm^2 (average) operation the current density ranged from 0.652 to 0.164 A/cm^2. The peak current density occurred at the spot where the current flowed radially out of the cell and where the fuel and oxidant entered the cell axially. The peak current density was two times higher than the average. Reducing the nonuniformity of the current density and thus of heat generation will reduce thermal stresses. These models will provide valuable aid in reducing potential stress failures and improving the performance of solid-oxide fuel cell electrical generators.

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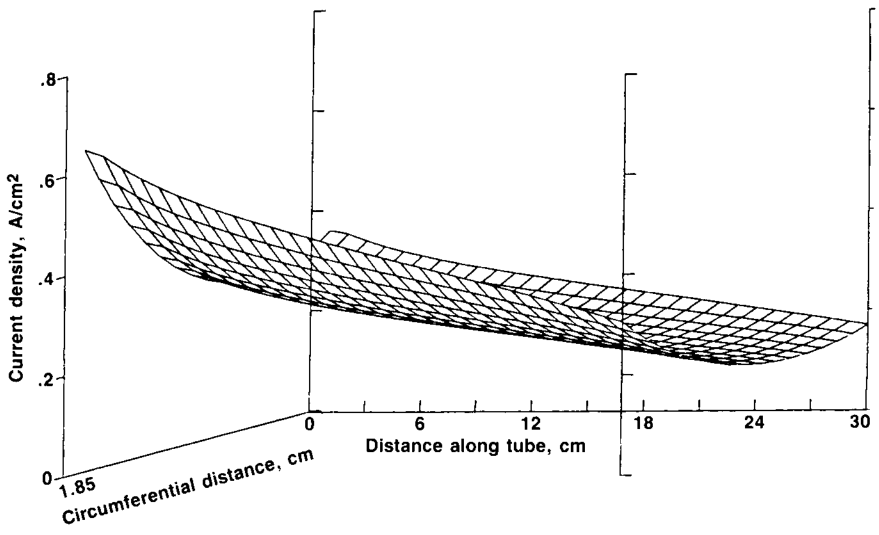
Funding source, DOE



Two-dimensional current density profile of tubular solid-oxide fuel cell

Automotive Stirling Engine

The automotive Stirling engine is being developed under a U.S. Department of Energy (DOE) program to develop the technology for an alternative automotive powerplant. Lewis manages the Automotive Stirling Engine (ASE) Program for the DOE. The prime contractor is Mechanical Technology, Inc. (MTI), and the major subcontractor supporting this effort is United Stirling AB of Sweden. The first-generation (MOD I) engines have completed development and seven MOD I engines have accumulated over 17 000 test hours. The technologies are now being incorporated into a second-generation (MOD II) engine.

Two MOD II engines have been fabricated and testing has begun. The MOD II engine is rated at 63 kW (84 hp) at 4000 rpm and operates at a combustion temperature of 820 °C. In 1988, after cell testing, the MOD II engine will be installed in a General Motors Celebrity vehicle to demonstrate its performance with respect to fuel economy, exhaust emissions, and drivability. The MOD II Celebrity is projected to have a combined EPA urban/highway fuel economy of 41 mpg with unleaded gasoline and an acceleration time of less than 13 sec (0 to 60 mph) and to meet all Federal emissions standards. The projected MOD II Celebrity fuel economy will represent a 50 percent improvement over the 1985 U.S. fleet average mileage for a 3000-lb inertia weight vehicle.

The automotive Stirling technologies are being considered for other applications. One of these applications is a Stirling-powered van. A MOD I engine installed in a van has been tested on the flight line at the Langley Air Force Base in Virginia. The van was operated for >1095 hr with various fuels: 443 hr with unleaded gasoline; 533 hr with JP4 (jet propulsion fuel, kerosene); and >129 hr with diesel fuel. After the performance data have been evaluated, the MOD I engine will be installed in a pickup truck and operated in service at several Air force bases.

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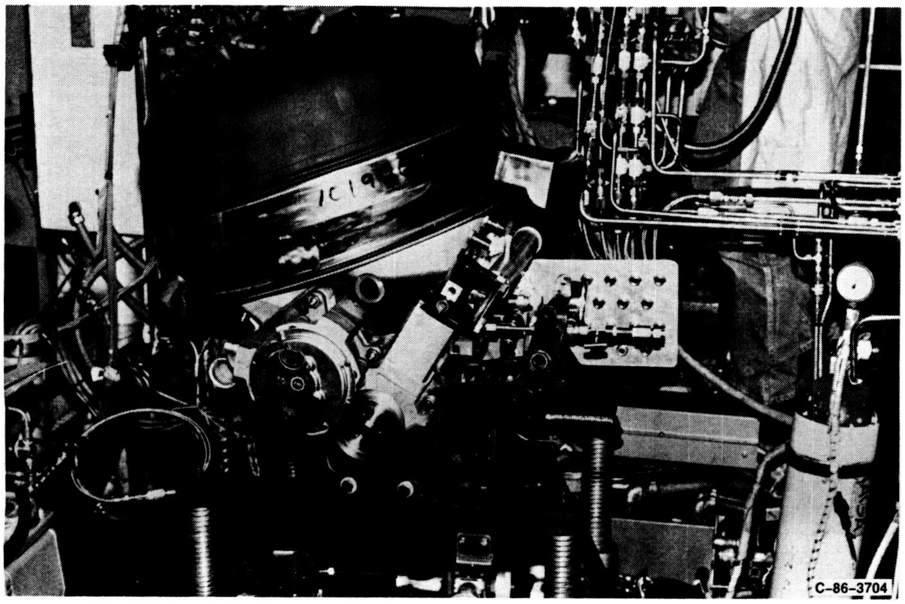

Automotive Stirling engine

Space Power Research Engine

After performance testing of the opposed-piston space power demonstrator engine (SPDE) was completed, the SPDE was divided to form two single-piston space power research engines (SPRE). One SPRE was retained by the contractor, Mechanical Technology, Inc., and the other was shipped to Lewis. The engines are being used to improve their components. This technology will also be applicable to the design of advanced Stirling space engines.

Testing of the first SPRE began in March 1987. Since that time a pressure-volume (PV) power level above 13 kW and a PV efficiency of the order of 22 percent have been achieved at a 20-mm piston stroke. The engine has an over-stroke capability that could increase the SPRE PV power level to greater than 15 kW (30 kW for the SPDE). Alternator efficiencies of the order of 70 percent have been measured—somewhat less than the design efficiency of 93 percent. Alternator diagnostic tests have determined that some structural elements which support the alternator are magnetic and become paths for magnetic flux leakage. This leakage in turn causes eddy currents in the structural elements and a loss of alternator power.

The following specific component technology improvement efforts are either under way or planned for the SPRE. The purpose of the work is to obtain design information for input into the advanced engines of the Stirling Space Engine Program:

(1) Substituting nonmagnetic and high-resistivity materials for the alternator support structure, and reconfiguring the support structure to define specific design changes needed to minimize alternator losses

(2) Reworking of the original SPDE hydrostatic gas bearing system to rotate the power piston for hydro-dynamic bearing support. A small permanent-magnet electric motor is used to rotate the piston. Initial testing showed that hydrodynamic bearing support of the power piston occurs at about 400 rpm. Less than 50 W of electric power is required to sustain the bearing.

(3) Designing and fabricating a modular heater head consisting of about 20 heater/regenerator/cooler modules for the SPRE in order to develop this new heater head technology for application to more advanced engines

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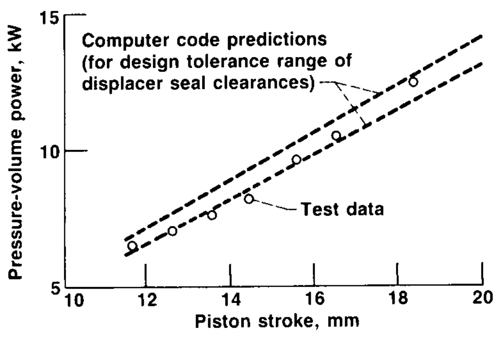
Space power research engine performance (engine pressure, 150 bar; pressure ratio, 2)



Durable High-Emittance Space Radiators

The ability of nuclear and solar dynamic power system radiators to efficiently radiate waste heat determines their area and weight. Lewis is investigating techniques to improve the emittance of radiator surfaces with the objective of developing durable high-emittance radiators suitable for use in low Earth orbit. Surfaces that are textured to improve emittance should be more resistant to emittance degradation caused by in-space contamination and atomic oxygen attack than are surfaces whose emittance is chemistry dependent. Discharge chamber triode sputtering, in which tantalum is simultaneously sputter deposited on the surfaces that are being sputter etched, has been demonstrated to produce high-emittance surface textures in radiator materials. Such microscopically textured surfaces have also been demonstrated to be durable to atomic oxygen attack.

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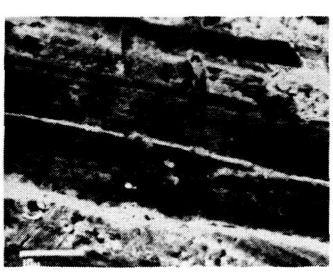
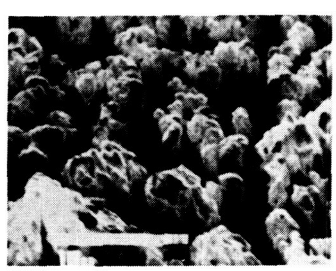
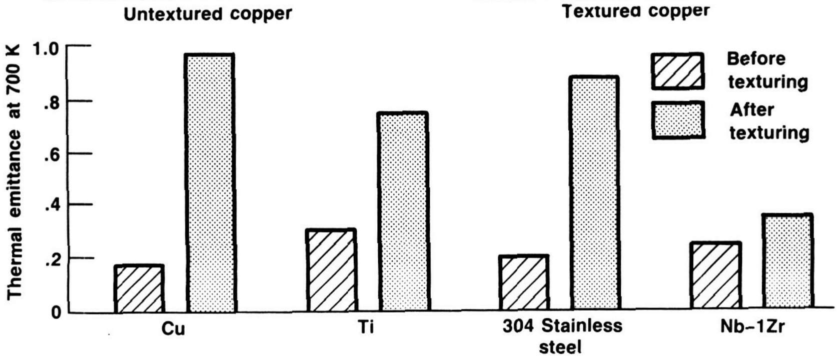
Radiator surface texturing for high emittance



Untextured copper



Textured copper



Space Communications

IR–100

Improved High-Emission-Current-Density, Long-Life Reservoir Cathode

Barium dispenser thermonic cathodes are necessary for reliable long-life operation of high-frequency, high-power tubes used in space and other applications, such as high-resolution radar systems. Potentially, a barium-oxide-reservoir type of dispenser cathode has a significantly longer operational life than the commonly used barium-impregnated type. Under a contract with Varian Associates a barium-oxide-reservoir cathode is being developed for operation at high current densities (to 10 A/cm^2) and extremely long life (100,000 hours or more). An important feature of this development is the use of a tungsten-osmium alloy surface for enhancing electron emission and reducing cathode operating temperatures. Other improvements in the technology include an osmium-rich, diffusion barrier layer for stabilizing the composition of the emitting surface, segregated tungsten powder for controlling barium flow from the reservoir to the surface, and a novel barium oxide encapsulation method to reduce the possibility of poisoning during cathode processing.

Tests of prototype cathodes have demonstrated an emission current density capability well beyond the original program goal of 10 A/cm^2 and possibly as high as 100 A/cm^2. The result is a cathode offering long-life operation over a broad range of current densities with a number of promising applications. These applications include

(1) High-frequency, high-power tubes for satellite-to-Earth, intersatellite, and deep space communications

(2) Microwave power transmission from satellites (e.g. to a Mars rover)

(3) Backward-wave oscillators for submillimeter-wave spectroscopy in space

(4) High-resolution, high-reliability radar systems for air traffic control and military applications

(5) Gyrotrons for plasma heating in fusion research and electric power generation

(6) Free electron lasers

Research & Development magazine has selected the improved high-emission-current-density, long-life reservoir cathode to receive an IR–100 award as one of the 100 most significant technical developments of 1987.

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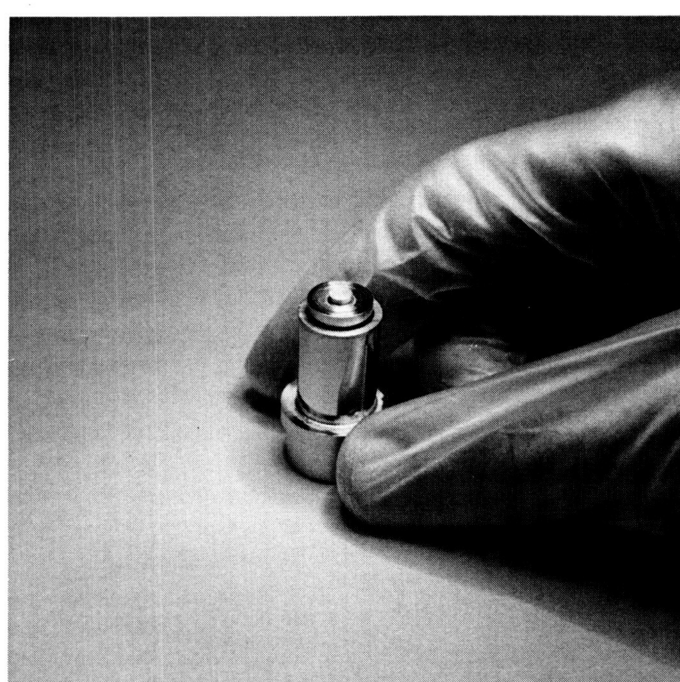


Barium-oxide-reservoir dispenser cathode

Numerical Arc Segmentation Algorithm for a Radio Conference

The Numerical Arc Segmentation Algorithm for a Radio Conference (NASARC) software package, developed by a team of Lewis engineers, is expected to be a major software tool in allotment planning for the fixed satellite service in certain frequency bands that is scheduled to take place at the 1988 World Administrative Radio Conference (WARC '88). The NASARC software package will allow planners at WARC '88 to satisfy the concerns of Third World countries regarding access to the geostationary orbit while providing the flexibility needed by the United States and other nations exploring advanced satellite technologies.

Computer software is required to solve large-scale, complex problems in satellite systems planning. NASA Lewis undertook the effort to develop software consistent with the U.S. need for flexibility in allotment planning, allowing for implementation of advanced satellite technologies.

Allotment planning for the fixed satellite service is to be conducted under the following guidelines:

(1) Each nation is to have guaranteed access to the orbit.

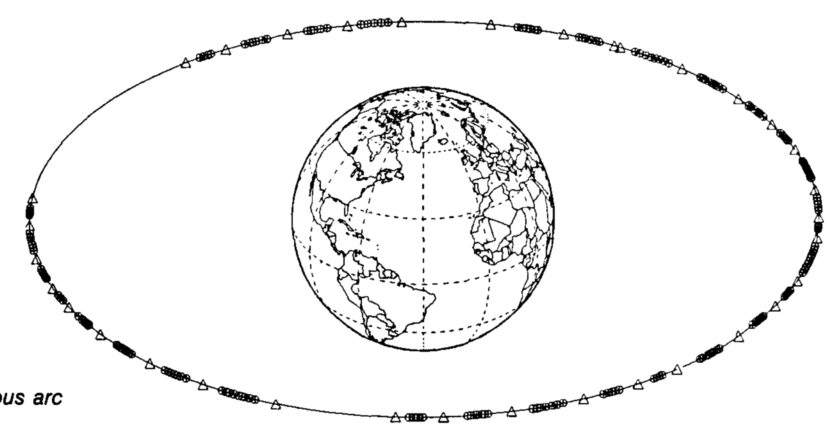
(2) Each nation is to receive an allotment consisting of a satellite orbital position within a predetermined arc.

(3) Each nation is to receive a full 800 MHz of frequency bandwidth in which to operate.

The predetermined arc is the key concept determining flexibility of orbital position. The concept implemented in the NASARC software defines predetermined arcs as arc segments to be shared by groups of "compatible" service areas whose satellites require little or no orbital separation in order to achieve a required downlink carrier-to-interference ratio *C/I*.

The NASARC software package consists of two major computer programs. The first determines an exhaustive list of compatible groups of satellite service areas and a potential predetermined arc segment over which each group may exist. Each compatible group consists of several service areas sufficiently separated geographically so that colocation or near colocation of their satellites will achieve a user-specified single-entry downlink *C/I*. The program operates on a set of basic requirements (including service areas, service arcs, and antenna beam dimensions) subject to a set of variable technical parameters (such as antenna gain patterns, target *C/I* ratio, and Earth antenna diameter) to assess compatibility between all possible pairs of satellite systems.

The second element of the NASARC software package uses a heuristic procedure to select an appropriate grouping, compute an allotted arc length, and place the group of compatible service areas in an open portion of the geostationary orbit, within the constraints of that group's available group arc. The



Satellites in geosynchronous arc

process is repeated until all service areas have been considered. This task requires groupings and predetermined arcs to be selected such that requirements of all service areas are met before the available orbital arc is exhausted. Thus the heuristic procedure employed preserves maximum flexibility for future allotments at interim stages of the algorithm.

The NASARC software has been installed and tested successfully by the International Frequency Registration Board (IFRB) in Geneva, Switzerland. The IFRB will use the NASARC software in planning exercises before the 1988 World Administrative Radio Conference.

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Systems Integration, Test, and Evaluation Project

The Systems Integration, Test, and Evaluation (SITE) Project uses a laboratory-based test facility to evaluate satellite communications system technology, including system design, component performance, hardware and software, and networking and control technology. The test facility, designed and built in-house, consists of a simulated satellite transponder integrated with high-data-rate digital ground terminals. Major components of the facility, such as high-power amplifiers and high-data-rate modems, are the result of hardware development contracts. The digital ground terminals and transponder integration are entirely in-house efforts.

The first phase of the project established a complete simulated satellite link. An extensive test program has evaluated the performance of numerous proof-of-concept components in a real digital transmission system environment. The results of these tests are currently being reported. The second phase of the project, now under way, will include multiple ground terminals operating in a time-division multiple access network and a radiative (30 and 20 GHz) link to a remote terminal.

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C-2

Radiofrequency Module for 406-MHz Search and Rescue Satellite-Aided Tracking Beacons

The Search and Rescue Satellite-Aided Tracking (SARSAT) Program has been instrumental in the successful rescue of more than 700 persons worldwide since the first launch of a SARSAT satellite in 1982. These rescues employed emergency beacons operating at 121.5/243 MHz, which all U.S. general aviation aircraft and certain classes of marine vessel are required to carry. Although considered highly successful, this satellite system has serious limitations. Thus a new frequency near 406 MHz has been assigned by international agreements for future development of distress beacons.

NASA has assumed the responsibility to assist in developing a low-cost, 406-MHz distress beacon. A contract for developing the radiofrequency (rf) module for this beacon is expected to be awarded in fiscal year 1988. This on-going technical effort seeks to establish a source of low-cost, high-efficiency modules for manufacturers of 406-MHz distress beacons. Each beacon manufacturer will develop a single beacon type on parallel contracts with identical specifications and will then deliver about 200 beacons to NASA. The module must perform to specifications with a minimum of adjustment and must be supplied in a simple, reliable package compatible with high-volume assembly and manufacturing techniques.

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High-Frequency, High-Power Cable

A 600-V, 60-A cable operating at 20 kHz has been developed by Induction General, Inc., under contract to Lewis. The cable has a power rating of 30 kW at a power factor of 0.85. It consists of three parallel flat Litz wire conductors; the center conductor is the power feed and the two outside conductors are the returns. This cable configuration has a low inductance impedance, which reduces the radiated electromagnetic interference. It will be used in large space power systems such as the space station. The cable may also be used in such ground-based power applications as high-power, high-frequency power supplies and induction heating machines.

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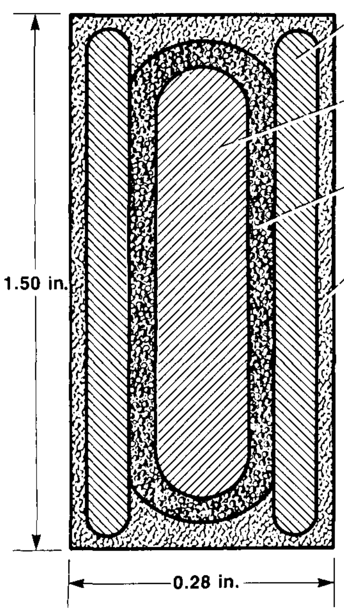

Remote Power Controller and Bus Isolator

A family of remote power controllers and bus isolators is being developed by Leach Corporation, under contract to Lewis, for high-frequency (20 kHz) distribution systems. The remote power controllers will protect the space station electrical system from a faulted load by limiting the current until the load is switched off. They will be remotely controlled to match particular load limits. The remote bus isolators will be used to reconfigure the main power buses in case of a bus failure. Both the remote power controllers and the remote bus isolators will provide status information such as voltage, current, voltage-current product sign, switch position, and last current reading. This information will be used to analyze the power system for load scheduling and system failures.

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Fast-Switching, High-Power Semiconductor

A 1200-V, 25-A semiconductor with a turnoff time of less than 1.5 msec is being developed by General Electric, under contract to Lewis. This semiconductor requires much less power to the base drive than existing semiconductors. Therefore fewer will be need for such space station components as dc-to-dc converters, dc-to-ac inverters, frequency changers, and remote power controllers. Fewer parts lead to greater reliability and reduced switching losses to greater efficiency for both the components and the space station system. This semiconductor can also be used in many ground-based power applications such as motor controllers, power conversion equipment, and high-power switches.

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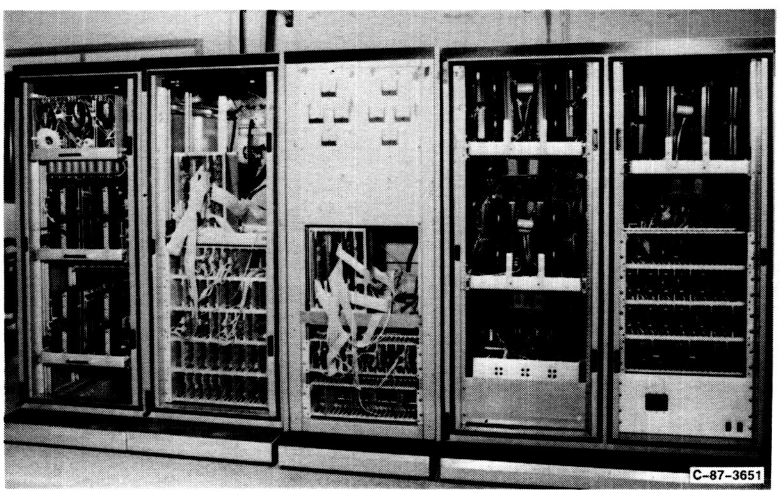
20-kHz ac testbed



20-kHz AC Testbed for Space Station Power System

Lewis has installed a 25-kW, 20-kHz ac testbed developed under contract by General Dynamics Space Systems Division. The testbed is configured to represent one side of the proposed space station power system. The system comprises multiple source converters, redundant reconfigurable 50-m transmission lines, remotely controllable bus isolation relays, power controllers, and variable-output ac and dc load converters. All control as well as system status monitoring is accomplished from a personal computer. Computer control of system configuration, set points, and load converters will provide a testbed for automatic power management, failure accommodation algorithms, and artificial intelligence studies. Additionally the testbed serves as a focal point for evaluating components developed under advanced development programs.

High-frequency distribution technology, together with autonomous power management, has a far-reaching effect on many proposed aerospace power systems including the Strategic Defense Initiative, Shuttle II, the National Aerospace Plane, commercial aviation systems, and helicopter control systems.

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Escort Data Acquisition System

Lewis has installed a new data acquisition system called Escort D. Escort D can acquire signals from a variety of instrumentation sources including analog measurements of temperatures, pressures, and other steady-state voltage inputs; frequency inputs to measure speed and flow; discrete input and output for significant events; and modular instrument systems such as multiplexed pressure modules or electronic instrumentation with an IEEE 488 interface. Escort D is designed to acquire data, convert them to engineering units, compute test-dependent performance calculations, limit-check selected channels or calculations, and display the information in alphanumeric or graphical form with a cycle time of 1 sec for the alphanumeric data.

This new system is the latest offspring in several generations of test-support systems. In the late 1970's Lewis developed a centralized data acquisition system that was named simply "Escort." Shortly thereafter the system was upgraded (to Escort II) to display as well as acquire data from small test facilities. Later Escort III was developed for the large wind tunnels and full-scale engine test facilities.

Escort D was designed to accommodate small to medium-sized test facilities. A faster scan rate will provide faster limit checking of engine conditions and allow real-time display of graphical information. Smaller, more powerful computers, high-density storage devices, low-cost hardware, and a need for secure data testing have combined to change the basic configuration of the new system from that of its predecessors. Escort D has a distributed architecture with a microcomputer located in each test facility. Each facility data system can therefore be a stand-alone system for secure data testing. The facility microcomputer is connected through a network to a centrally located computer cluster in the Research Analysis Center. During a research test the facility microcomputer performs as a stand-alone data system while executing all real-time tasks. The centrally located cluster is used for developing applications software, downloading developed software modules, uploading and storing facility tables and files, postrun data processing, and transmitting data to a data collector for archival storage.

The cluster consists of two mass storage subsystems connected to four computers through a star coupler. The four computers are nodes of a baseband local area network (LAN). The baseband coaxial cable provides the two-way communications path between the cluster and the facilities through the router.

The router is a minicomputer that connects directly to the coaxial cable. It is a dedicated communications system in the LAN that transfers messages from nodes of the LAN to remote nodes (facility microcomputers) and vice versa. Unshielded twisted-pair telephone lines connect the router to the test facility's microcomputer, with modems to transmit and receive the signals from the remote stations.

Two of the computers in the cluster are connected to the CATV laboratory data bus (broadband cable). The primary purpose of this connection is to provide a path from the test facility to a data collector for archival storage of research data readings.

The facility microcomputer acquires and stores the data readings locally on disk. The data are automatically off-loaded from the disk through the router to the cluster; the cluster forwards the data to a data collector for archival storage and later processing. For secure data testing, however, the link between the facility computer and the router is disconnected. In this mode all real-time tasks, data storage, and postrun processing are done on the facility computer in a secure environment.

Escort D is currently installed in five test facilities at Lewis. It is expected that approximately five new Escort D systems will be installed each year for the next 2 or 3 years.

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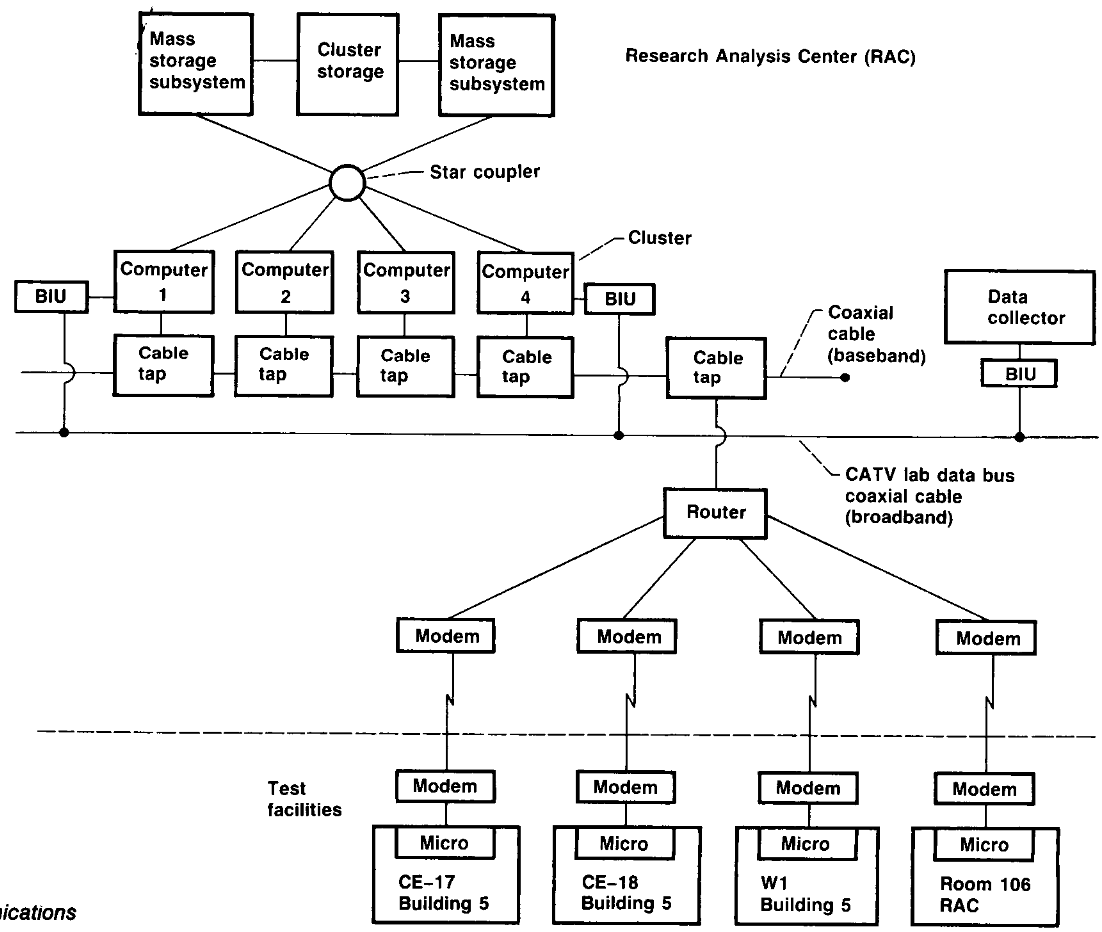

Design of Escort D communications